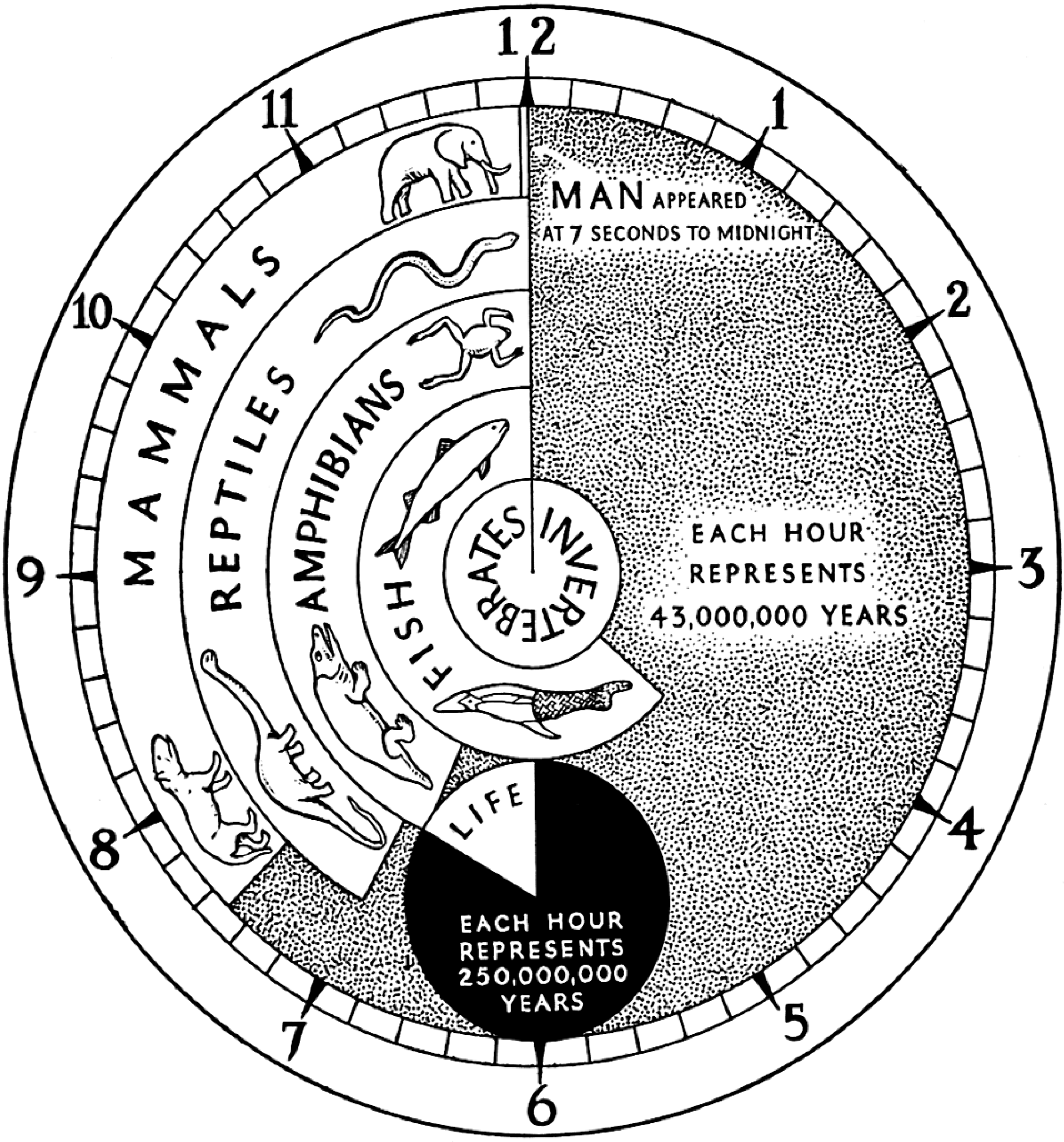
GENERAL PRINCIPLES OF GEOLOGY



THE GEOLOGICAL CLOCK

The smaller face represents the whole of Geological Time (3,000,000,000 years), the larger face only the last 520,000,000 years and this shows the time-range of the chief groups of Animals.

General Principles of Geology

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Preface

It is hoped that this book will provide a balanced introduction to Geology. The principles of the geological science were laid down by men who examined rocks 'in the field' (out of doors) and then attempted to account for what they had seen. The same method is followed here. The principles of the subject are not stated as facts, but are deduced, as far as possible, from descriptions of what can be seen at suitable places. The same deductive approach has been used throughout the book, for deduction from what can be observed either in the field or in the laboratory is not only the best method for attacking any geological problem, but is also a frame of mind in which anyone interested in geological matters should train himself from the start. The limitations of the space available have meant that statements of fact have been somewhat curtailed, especially as regards the description of large numbers of rocks, fossils and minerals. It is hoped that the principles of description and classification have been made clear, whilst further information can be obtained from the works listed in an appendix.

Although many of the basic principles of geological ideas were laid down more than 200 years ago, many of the most fundamental problems of Earth History still remain to be solved. These include the origin of the Earth and the nature of its interior, the origin of life and why forms of life have changed and developed during the geological past. There are many other unsolved problems and difficulties which are specifically geological, rather than relating to Science as a whole. These unsolved problems and difficulties have been stressed, but it is hoped not overstressed, in the following pages, for an introductory account should not give a misleadingly over-optimistic picture of our knowledge of Earth History.

The history of the Earth covers a very long period of time, at least 3,000,000,000 years. A geologist therefore has often to think in four dimensions; he has to see things 'in the solid' in the familiar length, breadth and height and, in addition, he has often to consider the time-aspect. The time-factor has also been emphasized wherever possible, commencing with the Frontispiece, in which it is shown that Man is very much a late comer in the geological sense.

He has only inhabited the Earth for the last million years or so, a span of existence less than one three-hundredth part of that of Fish.

But it is not only the forms of life that have changed during the geological past. The whole aspect of the Earth's surface has been constantly changing. Mountain ranges have risen from the seas, only to be slowly worn down and perhaps submerged again. One's appreciation of the scenery of today is considerably increased if one can think back in time and reconstruct the sequence of events which have led to the development of the present landscape and also if one's eye has been trained to detect those features by which the history and evolution of the land forms can be deduced.

Sincere thanks are due to my colleagues, Dr. E. H. T. Whitten and Mr. F. A. Middlemiss, for reading the typescript and for their criticisms and suggestions, to the publishers for all their help, especially with the illustrations, to the Geological Photographs Committee of the British Association and to Mr. J. R. D. Watts.

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CHAPTER I

The Development and Scope of Geology

A FORMER Prime Minister of England once described Geology as the great detective science, for the geologist is always searching the rocks of the Earth for clues and trying to reason from them.

Previous to the middle of the 18th century, only a few exceptional men, including that versatile genius Leonardo da Vinci, had studied seriously how the rocks of the Earth's crust had been formed, how they were arranged and how the different landscapes had been produced. The early philosophers had certainly produced many theories, but they were usually the result of armchair speculation, untrammelled by the evidence that could have been obtained by outdoor study or field work. Rigid acceptance of the Biblical story had also meant that the history of the Earth was regarded as extending over a few thousand instead of many millions of years.

Geology could not develop as a serious subject until men learnt to base their reasoning and speculation on field work. The adoption of this method by the founders of the subject meant rapid progress and by the early part of the 19th century most of the various branches of the subject, which are described below, had been established on a firm basis of deductive reasoning from field observations.

Physical Geology and Geomorphology

Many of the early geologists were very apt to invoke 'great convulsions of Nature' to account for anything which they could not easily explain. In 1795 a Scottish gentleman farmer, James Hutton, who is regarded as the founder of modern Geology, put forward very different views. In his *Theory of the Earth* he argued that the past can be understood by studying the processes that are

occurring at the present. The Huttonian principles were later summarized by Sir Charles Lyell in his dictum, 'The Present is the Key to the Past'. Lyell, who travelled very widely to see things for himself, was blessed with a facile pen and his *Principles of Geology*, first published in 1830, had a great influence on contemporary thought. *The Doctrine of Uniformitarianism* is still perhaps the main tenet of geological thought, though we now realize that it cannot be applied as rigidly as Hutton and Lyell thought.

The 19th century was a great period of exploration and the discoveries made profoundly affected geological ideas. Lyell, living near the sea, regarded wave attack as the chief agent in landscape formation by etching out differences in the hardness of rocks. In the 1870's, the Americans, J. W. Powell and G. K. Gilbert, published accounts of the Interior Basins of the United States and of the Colorado Canyon, and proved that rivers were just as potent an agent of landscape sculpture. The effects of ice were first studied in the Alpine glaciers by de Saussure (1740–1799) and Agassiz (1807–1873), but it was the exploration of Greenland and the Antarctic Ice Cap which provided the real clues for proving that ice caps, far greater than those of today, had once covered northern Europe and America and had profoundly modified the surfaces of these areas.

Well before the close of the 19th century, the main principles of *Physical Geology*, or the study of the processes effecting the Earth's surface today, were firmly established. The outlook was, however, rather static, insufficient attention being paid to the effect of time. The American W. M. Davis (1850–1934) changed this and by his concept of the Cycle of Erosion founded the modern science of *Geomorphology*, which regards the present landscape as but a stage in a series of changes, whose past can be deciphered and whose future can be, to some extent, predicted.

Petrology and Petrography

So far we have not considered the rocks out of which the landscape has been carved. The early geologists realized that many rocks, the *Sedimentary Rocks*, had been formed by the breaking down of pre-existing rocks, but they were very puzzled by the crystalline rocks like granite and basalt. One school of thought, the Neptunists, the followers of the German A. Werner (1749–1817), held that granite and basalt had been formed as chemical precipitates from a primaeval ocean. This view was based mainly on armchair reasoning, but when the Frenchman N. Desmarest (1725–1815)

and the German L. von Buch (1774–1853) studied in the field active volcanoes and also the recently extinct volcanoes of central France, they realized that basalt was similar to modern lava and must likewise have consolidated from a molten state. There were many fierce arguments before the Plutonists, such as Von Buch, with their field evidence, finally succeeded in overthrowing the theories of the Neptunists and establishing the true origin of the *Igneous Rocks.*

With the unaided eye it is often difficult to be sure that certain kinds of basalt are crystalline. *Petrology* or the study of rocks really began with the development, in the middle of the last century, of the petrological microscope with its Nicol prism for polarizing light. Just as Physical Geology has developed into Geomorphology, so with increased knowledge from experiments of the geochemical and geophysical behaviour of rock melts, Petrology, which is mainly descriptive, developed into *Petrography*, or the study of the conditions under which rocks were formed. Petrographers today are by no means in agreement as to the manner in which such a common rock as granite was formed, but fortunately their controversies are not fought so bitterly as were those between the Neptunists and the Plutonists.

Mineralogy and Crystallography

For thousands of years men have been attracted by the beautiful, rare and therefore valuable minerals which are to be found in certain places. When igneous rocks began to be studied properly it was found that they also are composed of aggregates of minerals. *Mineralogy* or the study of minerals, including both their description and their mode of occurrence and origin, is another branch of Geology that developed rapidly during the late 18th and early 19th centuries. *Crystallography* or the study of crystals was originally a subdivision of Mineralogy, but with the application of X-rays, the study of the detailed internal structure of crystals has become so specialized that advanced Crystallography is now more a branch of Physics than of Geology.

Stratigraphy

1815 is memorable not only for the battle of Waterloo, but also for the publication of the first geological map of England and Wales. This map was the work of a land surveyor, William Smith (1769–1839), who is known as the 'Father of English Geology'. On his map he had traced the outcrops, or areas where different rocks appear at the surface of the ground. Twenty years

later the first official Geological Survey, that of Great Britain, was founded. Since then the work of mapping the continents geologically has steadily continued and during the last hundred years all the more thickly populated, or economically important, areas of the World have been surveyed on the scale of, at least, one inch to the mile.

The preparation of geological maps soon showed that the rocks are not disposed haphazardly but they are, except in certain highly complicated areas, arranged in an orderly manner and that a definite succession of rocks can be made out. William Smith was nicknamed 'Strata Smith' by his contemporaries, for he elucidated the succession of the rock groups or strata of England. With the development of *Stratigraphical Geology*, it became necessary to produce a terminology for the different strata; a terminology that is now of world-wide application and which also has a chronological significance. This is dealt with more fully in Section E and we will only note here that rocks called, for example, Carboniferous in England and in the United States, were laid down during the same period of earth history, over 200 million years ago.

Palaeontology

As men mapped the rocks, they studied their characters and particularly any *fossils*, or traces of past life, which they contained. The existence of fossils had been known for hundreds of years, but the early philosophers had mostly regarded them as relics of Noah's flood or as placed by the Devil to mislead people. Smith in England and, at about the same time, Cuvier in France were the first to show that particular fossils were only to be found in certain strata. The natural inference was that rocks, however widely separated geographically, containing the same fossils, were laid down during the same period of geological time. Fossils, instead of being just objects of curiosity, were recognized to be of great value as time markers. Also by collecting the whole fossil assemblage from a particular stratum and applying Lyellian principles, it is reasonable to argue that as these fossils show many points of resemblance to forms living today under certain conditions, perhaps close inshore, therefore this particular bed must also have been formed in shallow water.

With maps showing the outcrops of the different rock groups and with fossil and other evidence as to whether the beds were laid down on land or in the sea, it became possible to construct *Palaeogeographical* maps, showing the geography of an area millions

of years ago. In Section F it will be shown that such maps are often of considerable economic value, for one can deduce from them the areas in which oil, water or perhaps certain minerals may be found.

Palaeontology, or the study of fossils, has another aspect. Fossils are the only evidence that we have of the great changes that have occurred during the last 500 million years in the forms of life that have inhabited the Earth. Many groups of organisms have become extinct during this long period and we are dependent for our knowledge of them on the palaeontologist studying their fossilized remains. These extinct groups include the giant reptiles, which about 100 million years ago dominated the Earth. Charles Darwin (1809–1882) obtained much of the evidence for his Theory of Evolution from the palaeontological record. Today we know many more evolutionary sequences, but the precise manner in which evolution proceeds is still actively debated, as is the manner in which life first appeared on the Earth.

Economic Geology

As the science of Geology developed, so its economic value grew and today *Economic Geology* is a most important branch of the subject. For example, the first oil fields were found from seepages of oil at the surface or by the sinking of 'wild cat' wells. Today oil field exploration is a highly scientific matter, with geologists using all their skill and knowledge to find places where there is a reasonable chance that drilling will be successful. Geologists have in recent years been joined by *Geophysicists*, who measure variation of gravity or of magnetism or plot the effects of explosions producing artificial earthquake waves, and so try to deduce the disposition of rocks deep beneath the surface of the ground.

Major engineering constructions used to be put up with a very large margin of safety and hence at considerably increased cost. Today thorough geological investigation of the site will give a much clearer picture of the difficulties likely to be encountered and the construction programme can be modified accordingly. Many geologists are employed by mining companies, whilst the Geological Surveys of the different countries always pay particular attention to occurrences of minerals or of any rocks, which may have an economic use.

SECTION A

Basic Principles

PLATE I

Stratification in the Lower Lias, Lyme Regis, Dorset

CHAPTER II

Stratification, Folds, Faults and Rocks

ROCKS exposed in quarries, railway cuttings, cliff sections or elsewhere are often seen to occur as definite layers or strata. Sometimes, as in the cliffs near Lyme Regis in Dorset (Plate I), the *stratification* is due to regular alternations of two obviously different kinds of rock. In most Chalk quarries, only one kind of rock is present, but careful examination shows that there are slight differences in colour, with the lighter coloured bands all parallel to one another and also to the lines of nodules of dark flint. The stratified nature of a mountainside is often revealed most clearly after snowfall, when the snow has settled thickly along certain layers.

In stratified rocks containing fossils, it will usually be found that the fossils are most numerous along certain layers. If the upper surface of one of the layers is exposed, the fossils will be seen to be lying flat, in the same way as one finds shells on a modern beach near low tide mark. In a sandpit one often finds layers consisting mainly of pebbles. One can imagine strong winds carrying sand across a pebbly beach or the stony surface of a desert and burying pebbles and stones with a layer of sand. The planes of stratification are therefore *bedding planes*, for they mark successive positions of the surface, perhaps a sea floor or a lake bottom or a desert, on which the material that now forms rocks was deposited.

If bedding planes are parallel, prominent and closely spaced the rock is said to be well-bedded, if they are rather indistinct and widely spaced it is poorly-bedded, whilst if they cannot be seen the rock is described as unbedded.

Rocks frequently show other planes at right angles to be bedding planes. This second set, known as *Joints*, are quite often open

fissures. As joint planes are not usually marked by the lines of fossils, pebble seams or films of clay, which so often occur along bedding planes, they must be of different origin. Rock material, as deposited on the sea floor, contains a considerable amount of water. As more material is piled upon a particular stratum, this water is gradually squeezed out, causing a reduction in volume of the bed. The amount of contraction that can take place in the thickness of the bed is limited but it can contract along its length by the opening of joint cracks. The spacing of the joints is determined by the

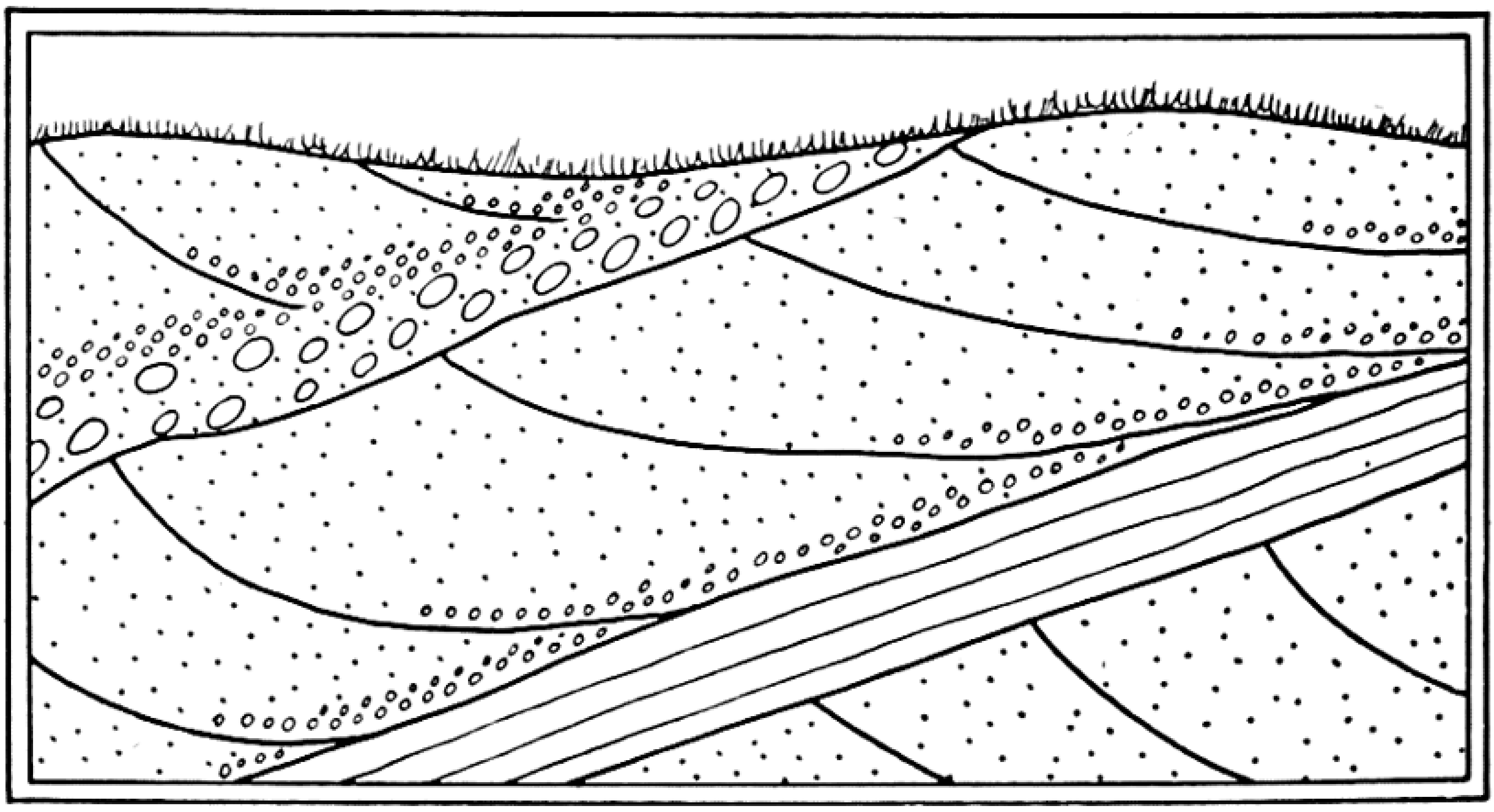


Fig. II, 1.—Sketch of a Sandpit Showing True Bedding and Current-Bedding

The seams of pebbles (ellipses) and of clay (parallel lines) mark the true dip at a low angle to the left. The layers of sand are strongly current-bedded at varying angles to the right.

nature of the rock. At Lyme Regis (Plate I), the harder beds are strongly or well-jointed with widely spaced open joints, whilst the intervening softer beds are more closely-jointed, being traversed by a multitude of tiny cracks.

Igneous rocks also contract as they cool from the molten state. The Giant's Causeway in Antrim is a superb example of this, the polygonal columns having been formed during the cooling of a great sheet of basalt (Plate II).

In sandpits, the slight colour changes that emphasize the bedding are often very confusing, the planes being inclined in different directions and at varying slopes. Careful examination will usually detect several seams of pebbles or films of clay, all roughly parallel and indicating the true bedding (Fig. II, 1). The planes

British Association photo

PLATE II

Polygonal Jointing in Basalt, Giant's Causeway, Antrim

of varying slope or *planes of false or current-bedding* were formed by currents or the wind, building up low banks of sand, down whose steep slopes sand grains rolled to come to rest at an angle to the sea floor or desert surface.

Dip and Strike

Strata are rarely perfectly horizontal but are usually inclined. The steepest angle made by the bedding with the horizontal is called the *angle of dip*. A bedding plane or stratum is said to dip at so many degrees in a certain direction. The direction of dip is

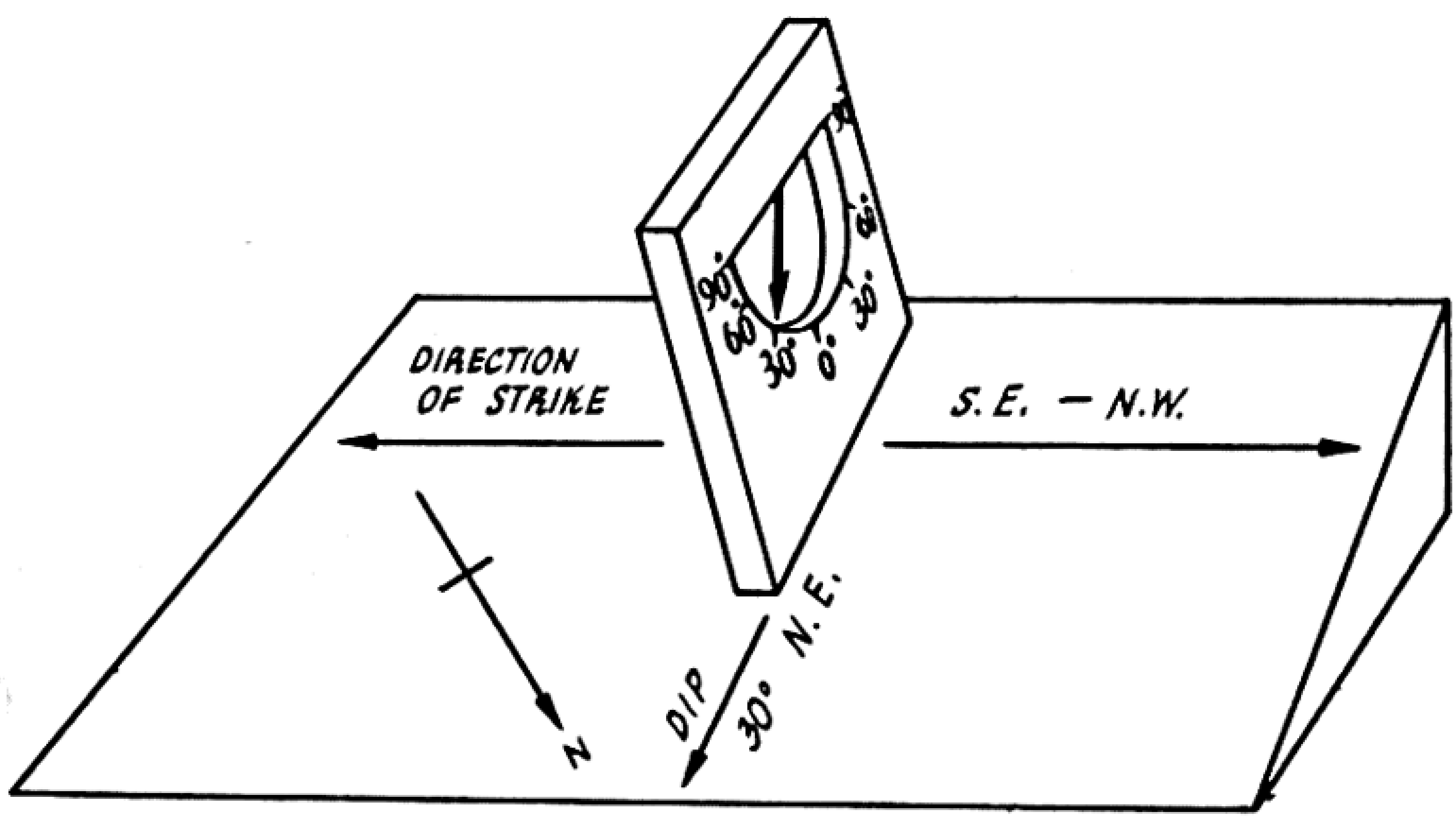


Fig. II, 2.—Measurement of Dip with a Clinometer
The bedding plane is sloping towards the observer and all left–right lines are horizontal.

measured with a compass and the amount with a clinometer. A horizontal line at right angles to the dip is called the direction of *strike*, so that a bed which dips north-east at 30° must strike south-east to north-west (Fig. II, 2). Just as one can draw contour lines on the surface of the ground, joining all points the same height above a datum, usually sea-level (M.S.L.) or Ordnance Datum (O.D.), so one can draw horizontal contour lines on the surface of a bed. These *stratum contours* are parallel to the direction of strike, so they are often called *strike lines.*

A bed is said to *outcrop* wherever it cuts the ground surface. The same term is used whether the bed is only an inch in thickness, and its outcrop can only be traced with difficulty along a line of rocks projecting through the turf, or whether it is hundreds of feet thick

like the Chalk with its outcrop forming a well marked topographic feature such as the North Downs. Outcrops extend parallel to the strike of beds, but the shape of the outcrop is a function of dip and the form of the ground. If a bed is horizontal, its outcrop must follow the contours of the ground. If, however, the bed dips, its outcrop cannot be parallel to the ground contours. A dip of 1°, which

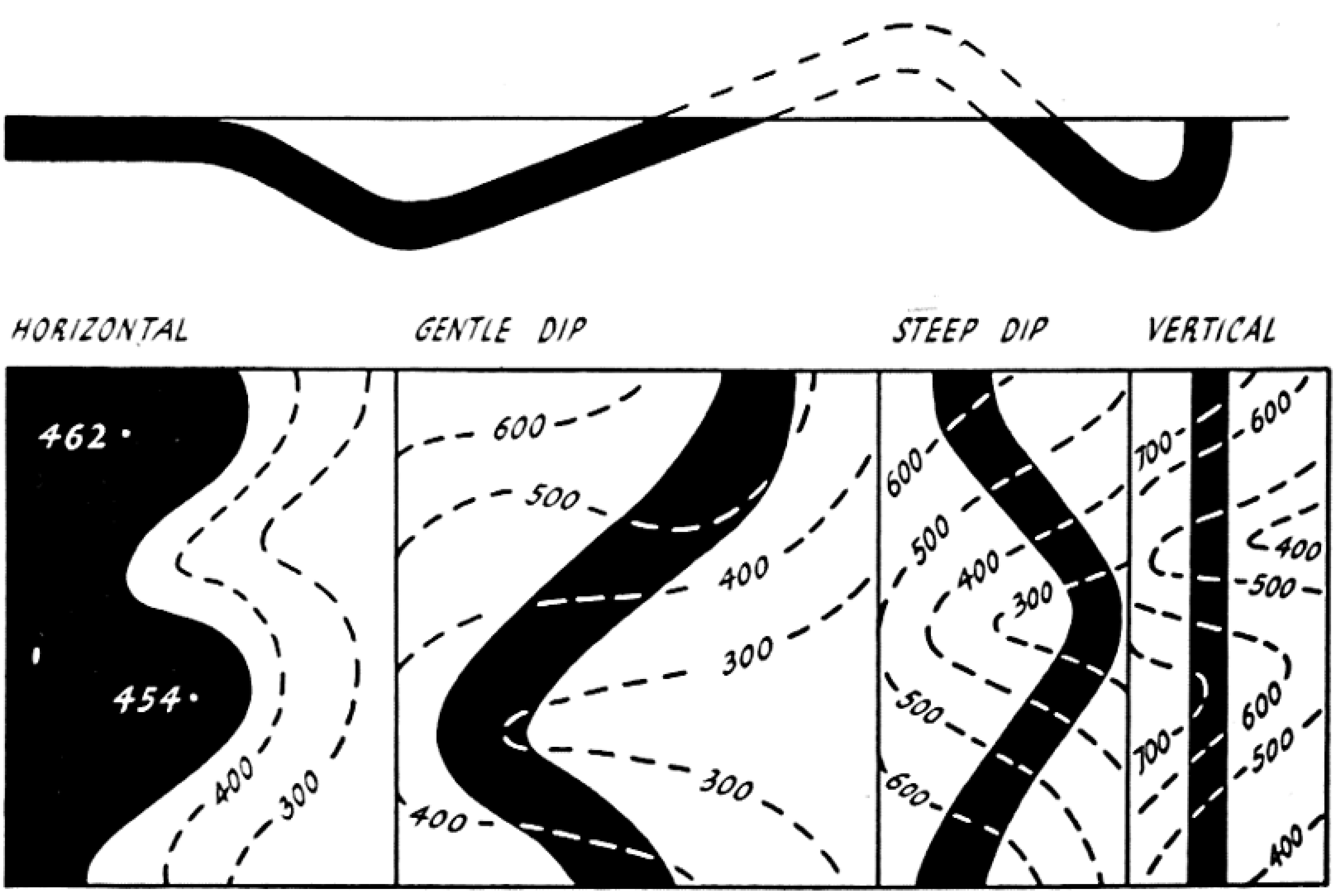


Fig. II, 3.—Effect of Change of Dip on Width and Form of Outcrop

The section above shows that with flat ground the width of outcrop of a bed of uniform thickness varies according to the angle of dip. In the maps below the broken lines are contour lines giving height above sea-level. Note that beds dipping into a valley 'V up the valley' and that a valleywards dip makes the beds 'V down the valley'.

is scarcely detectable by eye alone from true horizontality, means that the bed is sloping at nearly 100 feet per mile. Clearly the steeper the dip, the more rapidly will the bed change its level and its outcrop cross the ground contours, until when the bed is vertical (dipping at 90°) its outcrop must continue straight up a hillside. Change of dip will also affect the width of outcrop of a bed. A horizontal bed capping a flat topped hill may have an extensive outcrop, but with dipping strata the rule is *the steeper the dip, the straighter and narrower the outcrop* (Fig. II, 3).

On a geological map the outcrops of the different beds are

British Association photo

PLATE III

Unconformity between horizontal Jurassic limestones and steeply dipping Carboniferous Limestone, Vallis Vale, near Frome, Somerset

shown either by colour or by shading. If the ground is of low relief (nearly flat), the map is only two-dimensional, but if the relief is appreciable the map shows the disposition of the strata in three dimensions. With practice it is possible to read from a geological map the structure of the area, that is, the way in which the strata are arranged, and to construct geological sections, showing the shape of the ground and how the rocks would be seen to lie if a deep vertical cut could be made into the ground along a line (*See* Appendix I, Fig. XX, 3).

Unconformity

So far we have assumed that strata are parallel or *conformable* to one another. But this is not always the case. At Vallis Vale, near Frome in Somerset, quarries show a brownish rock, horizontally bedded, resting on greyish rocks dipping at about 45° (Plate III). If the contact between the two groups of rocks is examined, it is found that there are numerous pebbles of the grey rocks in the lowest few inches of the brown bed and also that the fossils yielded by the two beds are different. This difference in fossils proves that the brown and grey strata cannot be of the same age, whilst the pebbles show that the brown stratum must have been formed, in part at least, from the breaking down of the grey rocks. We have proved the *Law of Superposition*, that beds occur in *their order of formation with the younger rock resting on beds of greater age.*[1] We can also argue that the lower rocks must have been laid down, tilted at 45° and then worn away, before the younger beds were laid down horizontally across the bevelled edges of the older group.

Difference in dip between two groups of strata is called *Unconformity* and the younger beds are said to overlie the older rocks unconformably or with unconformity. The surface of contact between the two groups is a plane of unconformity. At Vallis Vale this surface is flat and a true plane, but at other places where beds are exposed in unconformable relationship the surface between them may be quite irregular.

Folding

Stratified rocks do not always lie horizontally or dip uniformly in one direction. They are often seen to be folded into upfolds (*anticlines*) and downfolds (*synclines*). When folds are cut across by the surface of the ground (Fig. II, 4) the beds outcrop as mirror

[1] Exceptions to this Law are discussed on p. 27.

images on either side of the fold axis, but in the *anticline* it is the *oldest* rocks and in the *syncline* the *youngest* which occur in the centre.

Folds may be symmetrical, like the gables of a house, with the same dip on either limb or they may be asymmetrical with one limb dipping the more steeply. If the axis of the fold is inclined, the fold is said to *pitch* towards the direction of inclination. A fold pitching at both ends can be compared to a canoe. As long as the keel (the axis) is horizontal, the two sides of the canoe (the outcrops) are parallel, but at the bow and stern, where the keel is inclined

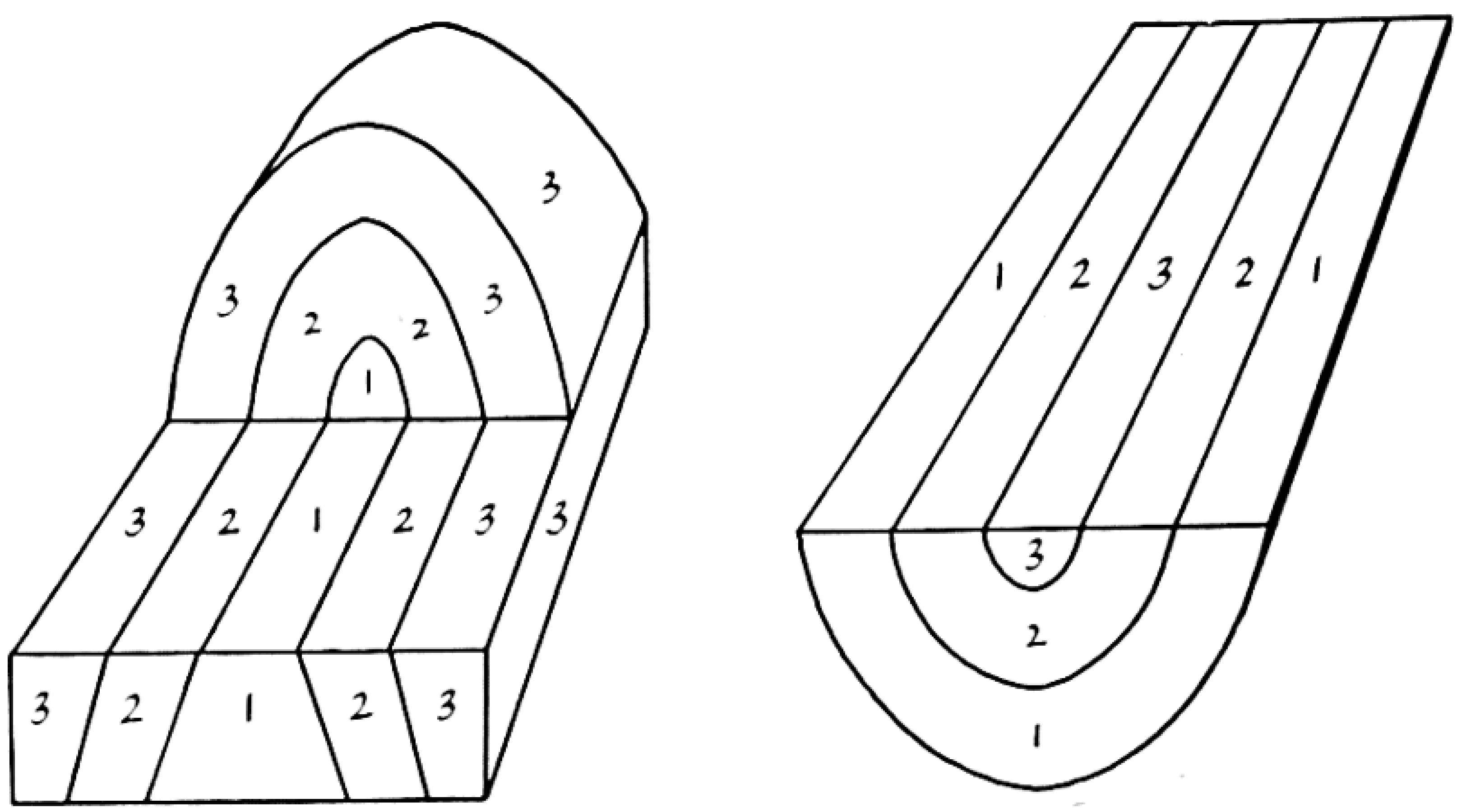


Fig. II, 4.—Block Diagrams of Anticline (*left*) and Syncline (*right*)

The beds are numbered in the order in which they were deposited.

(pitches), the sides of the canoe converge. An upturned canoe resembles a *dome* elongated along its length (a *pericline*) with the outcrops *converging down the pitch*, whilst the canoe in its normal position resembles an elongated basin with its sides diverging from the bow and stern posts, i.e. down the pitch of the axis.

Rocks were usually deposited as horizontal layers, but they have often been folded subsequently by the lateral pressure. The pressure has usually acted more strongly from one side than from the other, for asymmetry in folds is much more common than symmetry. In an asymmetrical fold the maximum pressure has come from the side towards which there is the gentler dip.

In Fig. II, 5, are shown the effects of increasing pressure on the form of folds. Commencing with a fold that is only slightly asymmetrical, increased pressure will produce greater asymmetry

until a *monocline* is formed with one limb vertical and the other dipping quite gently. Further pressure will push the crest of the fold forwards until it is in advance of the limbs and the fold has become *recumbent.* The axial plane of the fold will now be more or less parallel to the two limbs instead of being vertical as in a symmetrical fold or inclined less steeply than the limbs as in an asymmetrical fold. If the axial plane is nearly vertical, the recumbent fold is described as *isoclinal,* but with increased pressure the axial plane becomes more nearly horizontal with the formation of an *overfold.* When beds are overfolded, the strata on the upper limb of the fold lie in their order of deposition, but on the lower limb they are inverted and the Law of Superposition does not hold.

Rocks, when subjected to very strong pressures, do not behave like hot tar flowing into sweeping curves, but are usually brittle

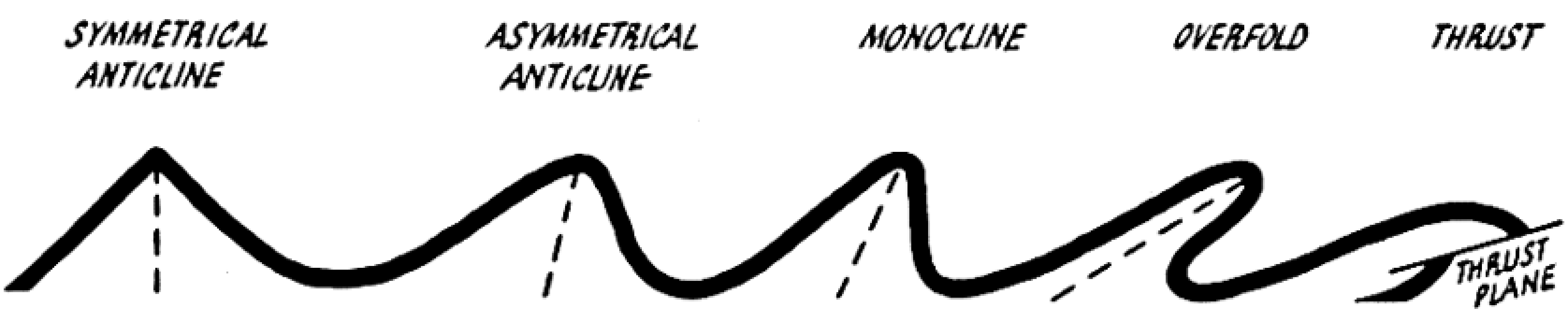


Fig. II, 5.—Effect of Increasing Pressure on Folds
Pressure increases towards the right until finally the folds fracture and are thrust. The dotted lines mark the axial plane of each fold.

and snap. In an overfold, the rocks may fracture along the axial plane and the normal limb will then be *thrust* over the inverted limb.

Such structures can occur on all scales. One can collect quite small pebbles showing perfect examples of thrusting or folding, whilst the North and South Downs, thirty miles apart, are formed by the Chalk outcropping on either side of the Wealden *anticlinorium.* The terms *anticlinorium* and *synclinorium* are applied to structures which are essentially anticlinal or synclinal, but whose limbs are not plane surfaces, but are composed of a number of small parallel folds. An analogy is a sheet of corrugated iron, which has been bent.

Faulting

Compression of one part of the Earth's crust must be relieved by tension elsewhere. One of the chief results of tension is *normal faulting.* Miners originated the term fault when, in following the

slope of a bed, they found that it had suddenly changed its level or had been 'faulted out'. This occurred at a steeply inclined plane of movement, the fault plane, along which one block had moved vertically relative to the adjacent block. The terminology applied to faults is shown on Fig. II, 6. The rule is that *normal faults always*

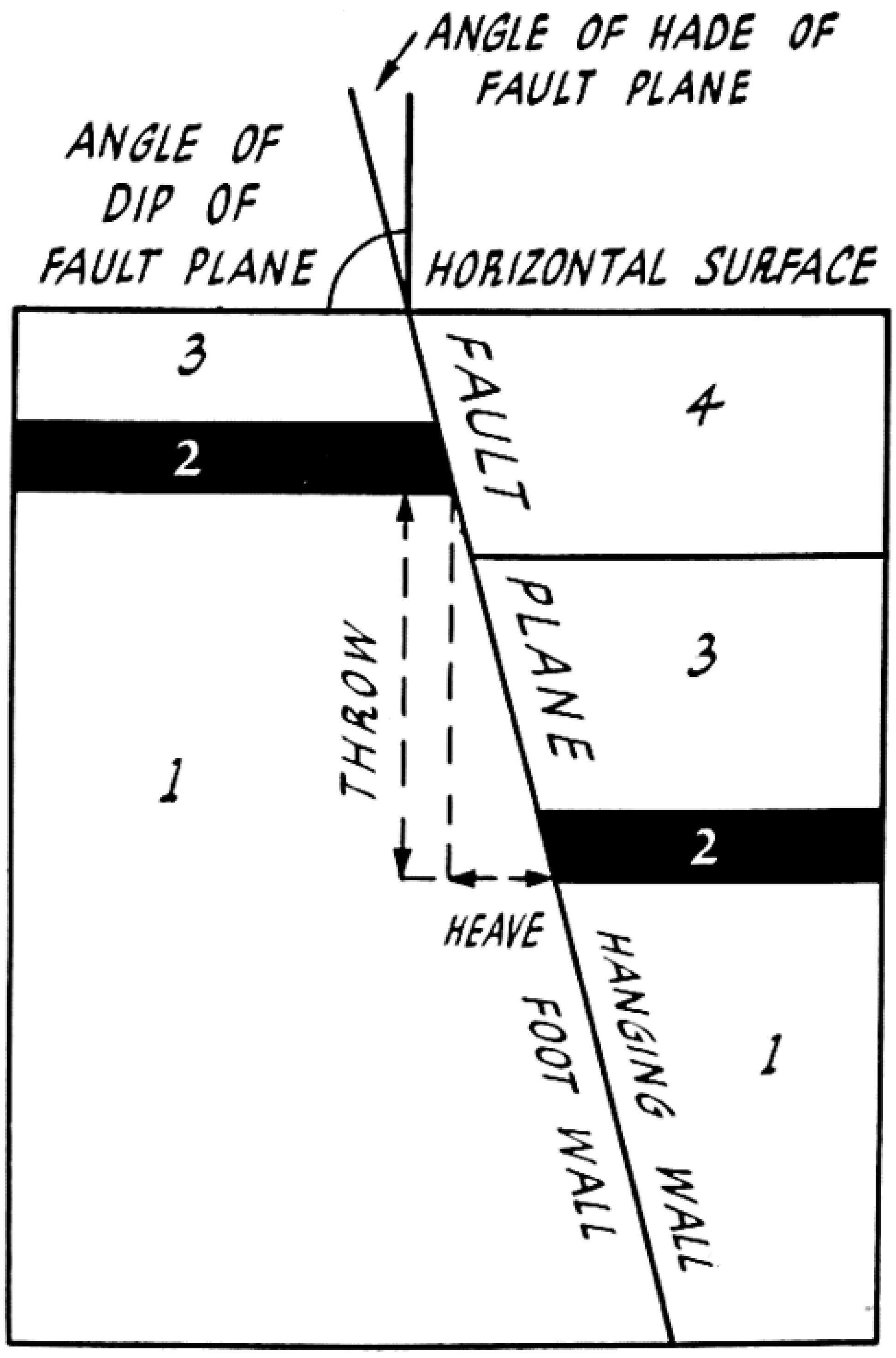


Fig. II, 6.—The Terminology of Faults

Note that 'hade' is measured from the vertical, that 'throw' is the vertical and 'heave' the horizontal displacement of the bed affected. The beds are numbered in order of deposition. As in all Normal Faults, the Fault Plane is hading towards the younger bed both at the ground surface and underground.

hade or are inclined towards the younger rocks. The vertical displacement or throw at a fault may be a matter of inches or as much as thousands of feet. Beds often show *terminal curvature* at a fault plane with the strata on the upthrown side dipping steeply downwards and those on the downthrown side as steeply upwards. This curvature is due to the drag of the two masses of rock past one another.

In a faulted area various structures may be produced, according to whether the faults throw towards or away from each other (Fig. II, 7). Faults very often form a rectangular pattern and if the rocks affected are dipping appreciably, we can classify the faults

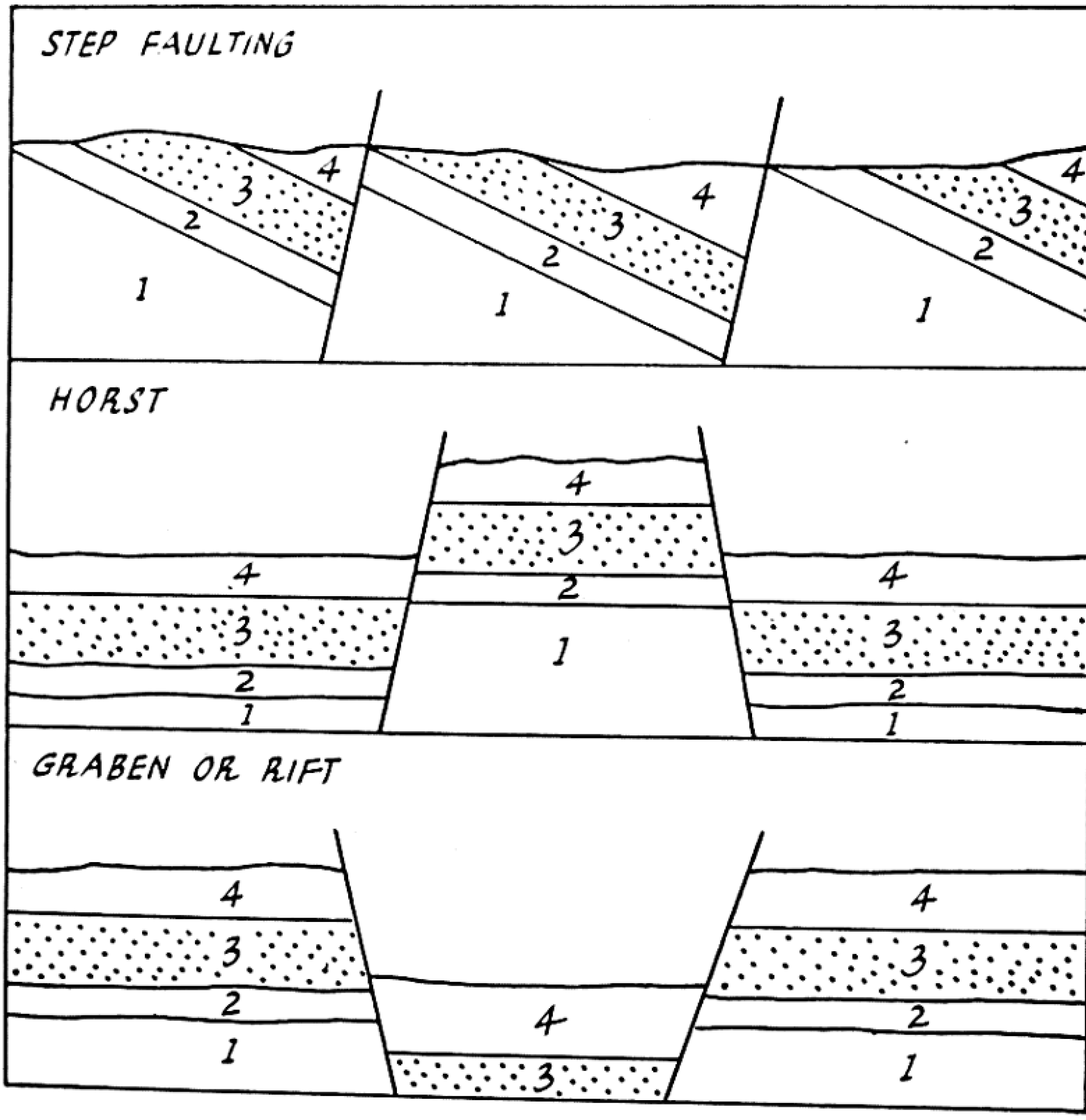


Fig. II, 7.—Structures Produced by Different Combinations of Faults

Note that the faults shown are all Normal Faults as they downthrow towards the younger beds. The beds are numbered in order of deposition.

as *dip faults* or *strike faults*, according to whether the fault planes are parallel to the dip or strike of the beds. The effect of dip faults is to shift the outcrops up the dip on the downthrow side of the fault, the amount of displacement depending on the throw of the fault, the dip of the beds and, to a less extent, on the form of the ground. The effect of strike faults on outcrops differs according to

whether the faults are throwing with or against the dip of the rocks. In the first case, there may be omission of strata, due to certain beds being faulted out and not appearing at the ground surface, whilst in the second case parts of the succession may outcrop on both sides of the fault (Fig. II, 8). The reader should work out for himself the effects of dip and strike faults on various types of folds.

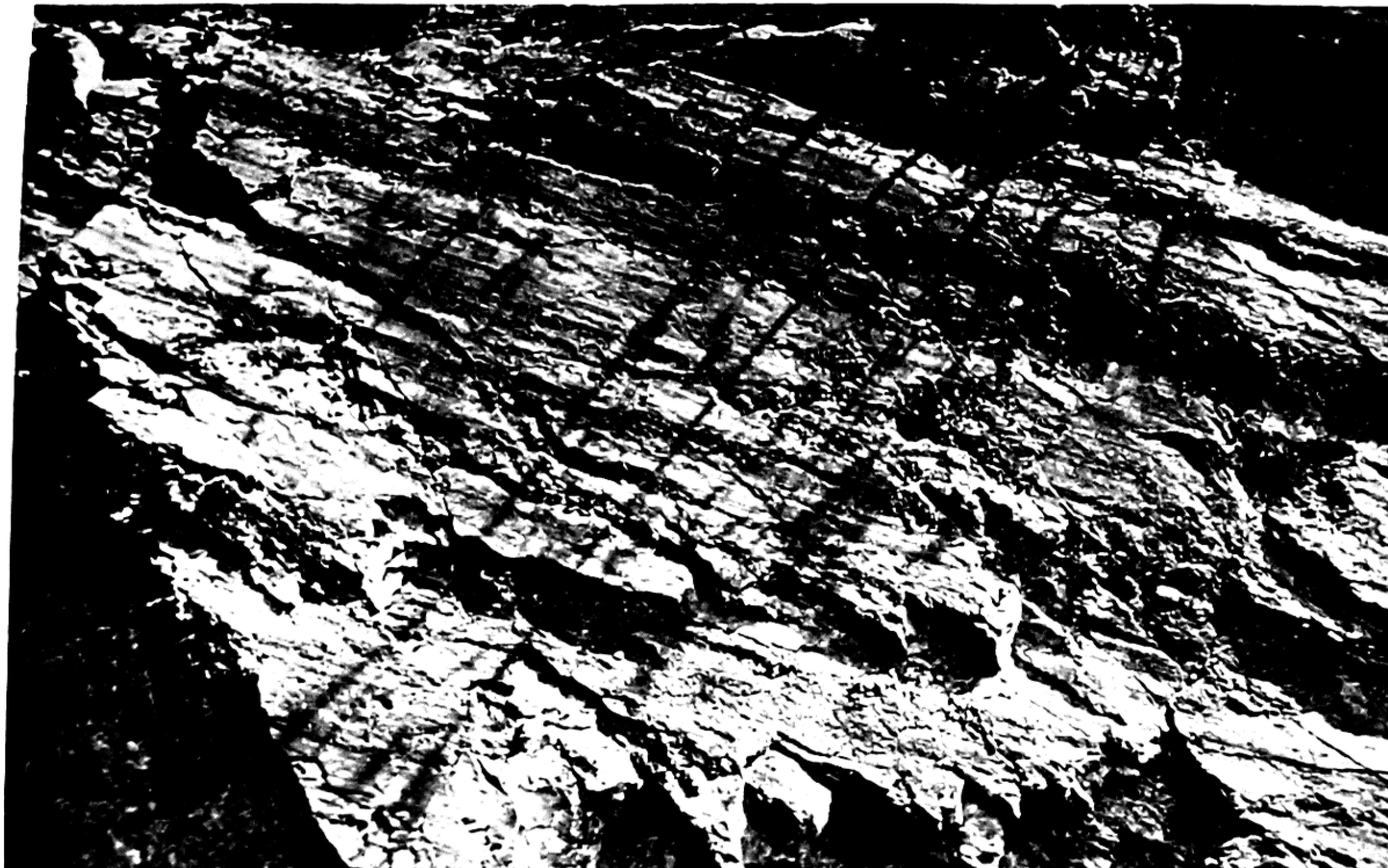
Less common are *oblique faults*, trending at about 45° to the strike of the beds. Their effect on outcrops is a combination of that due to dip and to strike faulting.

But not all faults are due to tension. Sometimes a fault plane is found to be inclined towards the older, not the younger, rocks, whilst the terminal curvature is the reverse of that found at normal faults. *Reversed faults* of this type are due to compression, the block containing the older rocks have been thrust over the younger rocks. In reversed faults the plane of movement is considerably more vertical than in thrusts. They occur in areas where the rocks have fractured, not folded, under pressure.

So far we have assumed that the movement along a fault plane must be vertical. This is usually, but not always, the case. *Tear faults* are produced when blocks move horizontally relative to each other, causing very considerable displacement of outcrop. It is often a difficult matter to decide whether a fault is a simple dip fault or a tear fault. If the fault plane is exposed, this may be possible. Large bodies of hard rock moving past one another must produce some effect. The fault plane is usually smoothed and polished by the friction, whilst any extra hard fragments in the blocks with cut striations or *slicken-sides*, which will show whether the movement was vertical or horizontal. If the fault plane is nowhere exposed (and this is quite often the case) it is very difficult to decide whether the main movement has been vertical or horizontal. A noncommittal term which gives the direction of displacement of outcrop, without implying the direction of movement, is to term faults *dextral* or *sinistral*, according to whether the outcrops on the far side of the fault plane have been shifted to the right or left hand of an observer facing the fault (Plate IV).

The Chief Types of Rocks

The stratified rocks are mainly the *Sedimentary Rocks*, formed by the deposition of material worn away from pre-existing rocks. The *Igneous Rocks*, on the other hand, have consolidated from molten material, *magma*, which has risen from great depths into the



J. R. D. Watts

PLATE IV

Slickensided surface of Carboniferous Limestone, Fall Hill Quarry, Ashover, Derbyshire. The low angle dip of the slickensides to the right shows the direction of movement. (The dark lines crossing the photograph are merely shadows)

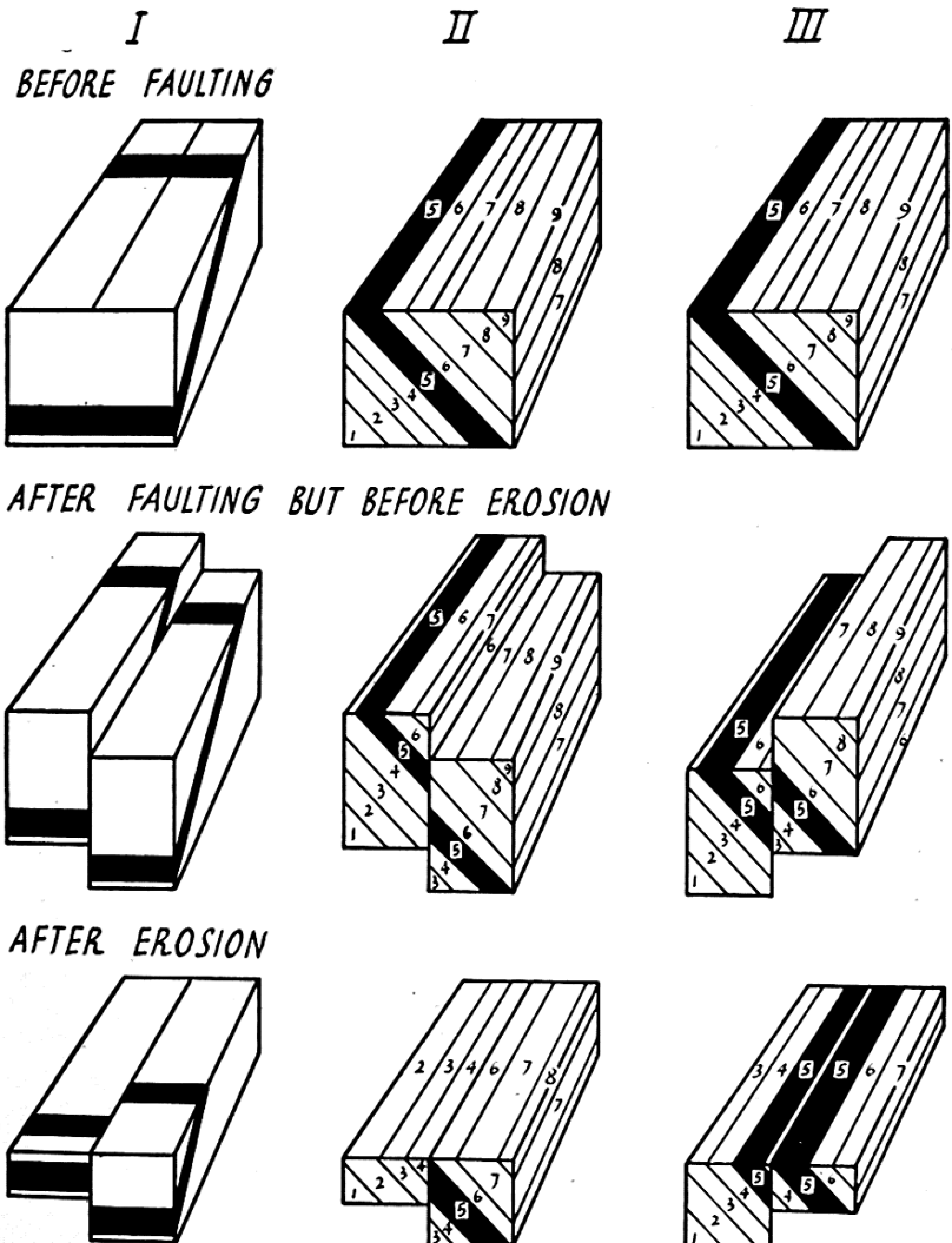


Fig. II, 8.—Block Diagrams to Show Some Effects of Faulting

I. Dip Fault shifting the outcrop 'up dip' on the downthrown side.
II. Strike Fault throwing *with* the dip producing omission of strata (Bed 5) at the surface.
III. Strike Fault throwing *against* the dip causing repetition of strata (Bed 5) at the surface.

cracks and weaker places of the stratified rocks or may have been poured out on to the surface from volcanoes.

We can classify masses of igneous rocks as *Concordant* or *Discordant* according to whether they are parallel to or cut across the bedding of the 'country' rocks. Concordant masses include sills and the sheets of lava and ash extruded from volcanoes. *Sills* are formed by magma which has risen up a fissure and has then spread out laterally along a plane of weakness parallel to the bedding of the country rocks.

The main discordant intrusions are dykes and batholiths. Faults are planes of weakness, up which magma can easily rise to form narrow sheets or *dykes*, which are perpendicular to the bedding. Sill-like tongues often extend for short distances from a dyke along the bedding. Individual dykes are sometimes traceable for a hundred miles or more, whilst in certain areas great numbers of parallel dykes form a *dyke swarm*. Such a swarm traverses part of the Isle of Arran, where in a 15-mile stretch of coast, 525 dykes have been measured with a total thickness of more than one mile, proving how great has been the stretching of the crust here and also the vast quantity of magma that has risen from depth.

Even larger discordant intrusions are the great *batholiths*, consisting of hundreds or even thousands of cubic miles of granite, which have forced their way into the country rocks. It is probable that Devon and Cornwall are underlain by such a batholith, the extensive granite outcrops of Dartmoor, Land's End and elsewhere being but its highest parts or *bosses* (Fig. X, 8).

Other large intrusions are *laccoliths*. In this case the magma, rising up a fissure, has met a particularly resistant stratum and whilst it has been able to arch this into a low dome, it has been forced to spread out laterally beneath this bed (Fig. II, 9).

There is another major group of rocks, the *Metamorphic Rocks*; sedimentary or igneous rocks altered by heat or pressure or both. The heat contained by a granite batholith will bake and alter the country rocks with the formation of a *metamorphic aureole* of *thermally* metamorphosed rocks. Rocks subjected to pressures sufficiently great to produce large-scale overfolding and thrusting will attempt to occupy less volume. New minerals of higher density will be formed and the rocks will be *dynamically* metamorphosed. The pressures and temperatures may be sufficiently high for the rock material to flow rather than fracture, so we find that metamorphic rocks of those type often show a pseudo-stratification or *schistosity*, being

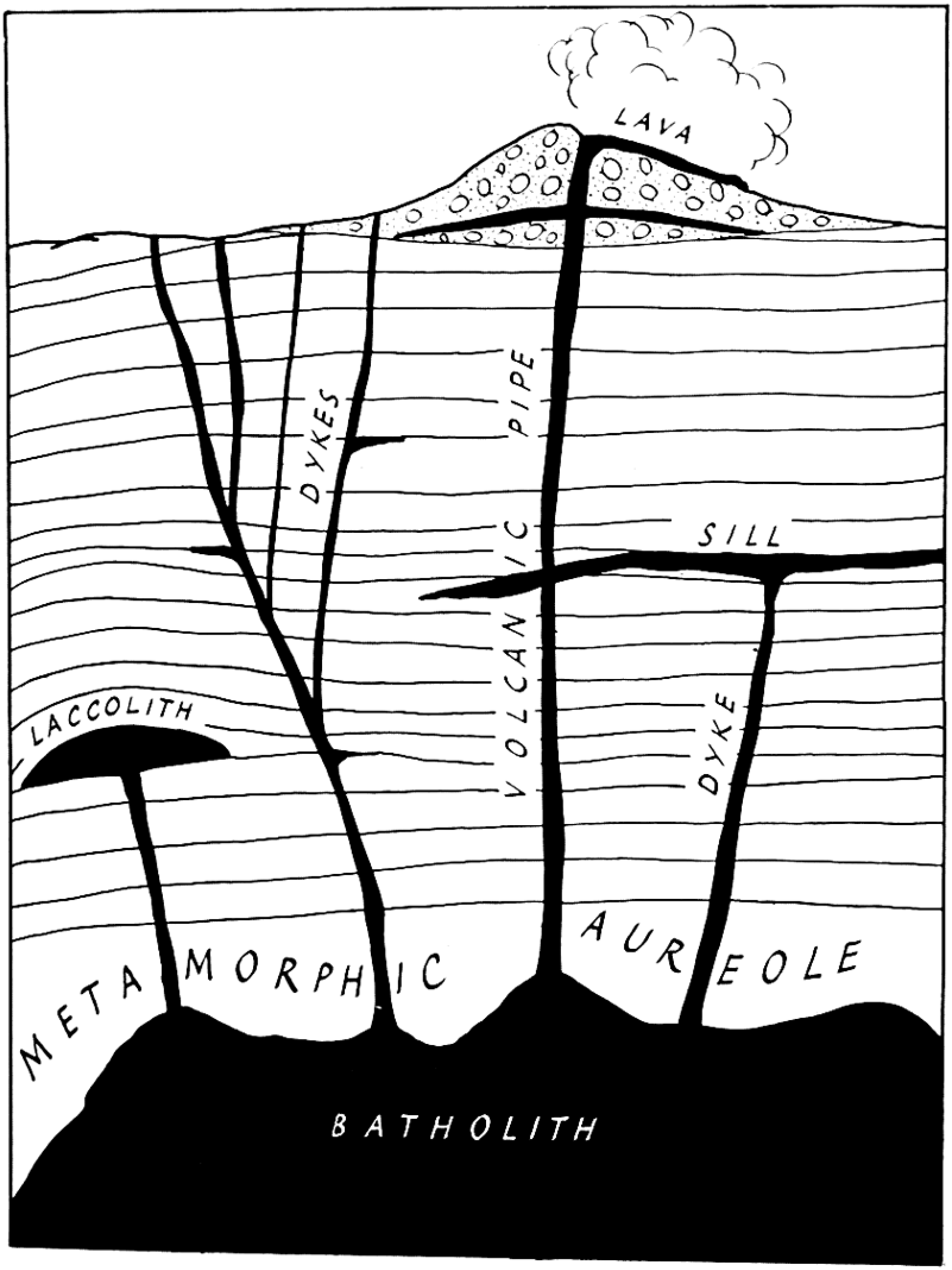


Fig. II, 9.—FORMS OF BODIES OF IGNEOUS ROCKS

A batholith intruded into horizontally bedded 'country rock' has a wide metamorphic aureole. Magma has risen up fissures to form from left to right:

A. a laccolith;
B. a group of dykes;
C. a volcano composed of alternating layers of pyroclastic material, thrown out by explosions, and lava flows. Note that the coarsest material fell nearest to the crater;
D. a sill, which is slightly discordant at its left-hand end, for it cuts across the bedding planes.

The volcanic pipe cuts through the sill and therefore the sill must have been intruded before the opening of the pipe.

traversed by innumerable slightly curving planes along which a certain amount of lateral movement has occurred, whilst the minerals are often elongated in the same direction (Fig. II, 10).

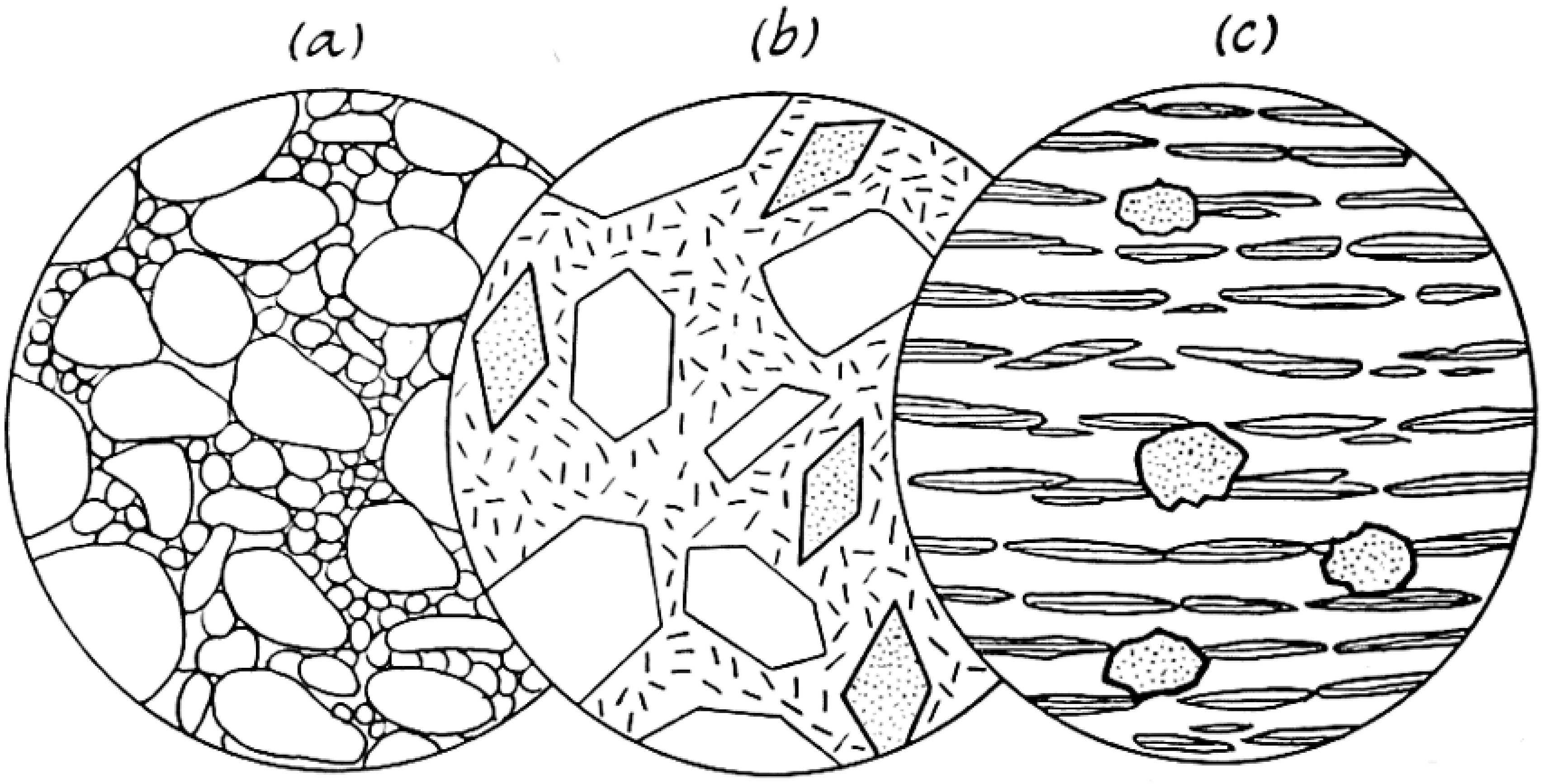


Fig. II, 10.—TEXTURES OF TYPICAL (a) SEDIMENTARY, (b) IGNEOUS AND (c) METAMORPHIC ROCKS

Note the rounded shape of many of the fragments forming the sedimentary rock, the well-formed crystals of the igneous and the schistose nature of the metamorphic rock.

SECTION B

Physical Geology and Geomorphology

INTRODUCTION

DENUDATION or the wearing away of the Earth's crust proceeds in three stages. First rocks are broken down at their outcrop by the processes of *Weathering*, either into fragments, which are transported away by gravity, moving water, ice or the wind, or they are changed into a form which can be removed in solution. The products of rock weathering are eventually deposited in the depressions of the Earth's crust to form new sedimentary rocks. During *Transportation* the rock fragments abrade and erode the strata across which they are being carried. We speak of river *Erosion*, marine erosion, glacial erosion and wind erosion according to whether the transported rock fragments have acted as the tools for the abrading action of rivers, waves, ice or the wind.

Denudation normally acts so slowly that, human interference apart, the land forms of an area show no appreciable change during a human lifetime. But every now and then an abnormal combination of circumstances produces a tremendous acceleration of the rate of denudation. An instance is the floods that swept down the rivers of Exmoor on the night of August 15th, 1952, and carried away many of the houses and inhabitants of Lynmouth and left the streets of the wrecked township piled high with great boulders.

Geological time is measured not in tens but in millions of years. During this vast period the agents of denudation have been ceaselessly at work, and by processes which will be described in the succeeding chapters great mountain chains have been worn away not once, but many times.

Whilst it is necessary here to deal separately with weathering, transportation, erosion and deposition, it cannot be too strongly emphasized that there is no such clear cut division in nature. The balance that determines whether a river will, at a particular spot, erode its bed or deposit part of its load, is an exceedingly delicate one. In studying the land forms of a particular area, one has to analyse the interplay of numerous factors and decide which are dominant.

CHAPTER III

Weathering of Rocks

WEATHERING may be due to chemical, physical or organic agents. We will consider each of these separately, but in an actual case a combination of these agents is normally acting, though one of them is usually dominant.

CHEMICAL WEATHERING

Rain water is never absolutely pure. Whilst falling through the atmosphere, it dissolves small quantities of various gases and reaches the ground as a very dilute solution of carbonic, nitric and, in industrial areas, sulphuric acids. Decomposing vegetation adds the humic acids. This acid-charged water penetrates into the cracks and crannies of the rocks and attacks them in various ways. Limestone, composed of calcium carbonate, is the rock most easily attacked, the carbonate being converted into the bicarbonate, which is soluble and can be carried away in solution, e.g.

$$CaCO_3 + H_2O + CO_2 \rightarrow Ca(HCO_3)_2$$

It has been estimated that the River Thames carries past London every year 350,000 tons of calcium bicarbonate, which has been dissolved by the rain falling on the Chalk of its drainage basin.

In some limestone areas the effects of *solution* are most spectacular. In the Pennines, particularly around Ingleborough, are to be found many 'limestone pavements', with the joint pattern widened by solution to form 'grikes' or 'clints' (Plate V). But the greatest effects of solution are usually hidden below ground level. Water pouring down 'swallow holes' or greatly widened joints, such as Gaping Ghyll, has dissolved out great underground caverns,

British Association photo

PLATE V

Grike surface of Carboniferous Limestone, Malham, Yorkshire

some large enough to contain a cathedral. The very distinctive land forms of Karst topography, which result from the prolonged solution of limestones, are described later (p. 63).

Limestones always contain some insoluble material, such as the flints of the Chalk. As the surface of a limestone area is lowered by chemical weathering, this insoluble material accumulates to form the 'Clay-with-Flints' of our Chalk lands or the 'Terra Rosa' of the true Karst. Such deposits are known as *residual deposits*, for they are the residues left behind after the solution of vast quantities of limestone and are a direct result of chemical weathering.

Even such a hard rock as granite is attacked by solution, though much more slowly than limestone. Granite is composed mainly of three minerals, quartz and mica, which are almost insoluble, and feldspar, which becomes partly soluble.

$$\underset{\text{Feldspar}}{2KAlSi_3O_8} + 2H_2O + CO_2 \rightarrow \underset{\text{Kaolinite}}{H_4Al_2Si_2O_9} + \underset{\text{Quartz}}{4SiO_2} + K_2CO_3$$

The potassium carbonate is removed in solution, the clay mineral kaolinite and the quartz being left behind. At the top of many old quarries on Dartmoor is a thickness of deeply weathered granite. This rotted granite appears from a distance to be quite solid, but it crumbles in the fingers, for the feldspar crystals have all been altered to soft kaolinite.

Chemical weathering affects rocks in other ways as well. Many rocks, particularly igneous and metamorphic rocks, contain silicate minerals, composed in part of ferrous iron. Weathering breaks up the complex molecules of the silicate minerals, as in the case of the feldspar given above, and the ferrous iron is *oxidized* to the ferric state, forming a brown or yellow crust to the rock. A geologist uses his hammer to break through this weathered crust, so that he can examine the fresh (unaltered) rock beneath. The ferric compounds often absorb further water to become one of the hydrated salts of iron. Only small quantities of these iron hydrates are needed to colour the rocks various shades of brown, yellow or red and, in general, the deeper the colour the more intense the degree of weathering. Sulphides are also affected, being oxidized first to sulphates and then to hydrates. So widespread are iron compounds in rocks and so striking are the effects of their weathering, that iron has justly been termed 'Nature's chief pigment'.

The reverse process *reduction*, or loss of oxygen, is naturally much less common, but does occur when percolating water is

highly charged with humic acids. Then the ferric compounds are reduced to the ferrous state. Small white or green spots can often be seen in the upper parts of a red or brown sand or clay rock. Careful examination will often show that these 'reduction patches' are centred round the roots of trees, which can penetrate downwards for a surprising distance from the surface.

Hydration can affect other minerals than the silicates. For example:

$$\underset{\text{Anhydrite}}{CaSO_4} + 2H_2O \rightarrow \underset{\text{Gypsum}}{CaSO_4 . 2H_2O}$$

In this case the absorbed water produces an increase in volume of about 33 per cent, so that the rocks surrounding the gypsum are often shattered by its expansion and are rendered more easily removable by other agents.

Chemical weathering therefore either breaks rocks down into soluble compounds which can be removed in solution or so weakens the rocks that they can be attacked more easily by the other agents of weathering.

The rate of chemical weathering is not uniform over the World. It is at its minimum in high latitudes and at high altitudes, where temperatures are low and there is little water in the liquid state. It is at its maximum in low latitudes, especially where rainfall is abundant and the high temperatures accelerate the speed of the chemical reactions. In many parts of the tropics geologists wishing to examine fresh rock cannot break through the weathered crust with the blow of a hammer, as they can in temperate latitudes, but have to sink pits through many feet of weathered material.

The residual deposits formed by chemical weathering under tropical conditions are known as *laterites* and *bauxites*. So intense have been the reactions, that much of the silica of the silicate minerals has gone into solution, only the insoluble hydrates of ferric iron and alumina remaining. If iron is in excess the porous red-brown rock is known as laterite, but if the rock is lighter coloured with the aluminous compounds dominant, it is termed a bauxite and may be rich enough to be worked as an ore of aluminium. So specialized are the conditions producing laterites and bauxites that we can use their occasional presence in the stratified rocks as evidence for the former existence of tropical conditions. Visitors to the Giant's Causeway in Antrim cannot help noticing the vivid

British Association photo

PLATE VI

Spheroidal Weathering in Basalt, Giant's Causeway, Antrim

red layer which separates the upper columnar from the lower more massive basalts. Examination shows that the upper 20 or 30 feet of the lower basalts have been lateritized. This 'Inter-Basaltic Horizon', which can be traced all round the lava plateaux of Antrim, proves that after the outpouring of the lower basalts, there must have been a period of tropical weathering under monsoonal conditions, before the extrusion of the upper basalts. Lateritization is known to be a very slow process and it has been estimated that this bed, 20 to 30 feet in thickness, may represent a period of a million years. At the Giant's Causeway, this lateritic horizon is composed of sphaeroidal masses, with a core of almost unaltered basalt, surrounded by successive skins of more and more weathered material, the sphaeroids being separated by structureless laterite. Sphaeroidal or *Onion Skin Weathering* of this type is developed in well-jointed rocks. Water penetrating down the vertical and along the horizontal joints has attacked the corners of each block. The corners were soon weathered away, forming convex surfaces, and as each weathered crust split off, concentric skins like those of an onion were formed (Plate VI).

Physical Weathering

The shattering of rocks by physical or, as it is sometimes called, mechanical weathering, is chiefly due to changes of temperature. When temperatures are fluctuating around freezing point, the 'frost wedge' begins to act. Water expands by one-tenth of its volume when it freezes, exerting a pressure of about 2000 pounds per square inch; a fact that is often disastrously demonstrated by domestic water pipes after a severe frost. If the fissures of a rock contain water the stresses set up by repeated freezing and thawing will eventually shatter the rock. If one is amongst the High Alps on a sunny day one can hear and watch the constant rain of fragments down the crags, as the sun's warmth melts the ice which has been holding in place the blocks wedged off by the previous night's frost. These blocks, of all shapes and sizes, form at the foot of the cliffs, a scree or talus slope. The fragments have little or no weathered crust, for at such low temperatures chemical weathering is inappreciable. In the mountains the action of the frost wedge is shown not only by the presence of screes but also by the ridges of hard rocks which have been fretted into needle-like arêtes. Frost shattering therefore occurs everywhere above and, according to the amount of precipitation and the number of night frosts, for some distance below the snow line.

In the hot deserts and in regions where there is a long and

hot dry season the bare rocks are exposed to temperatures that range from well above 100°F. during the day to nearly freezing point at night. Such a large diurnal variation of temperature shatters rocks by the differential expansion and contraction of their constituent minerals. Rocks are poor conductors of heat and therefore whilst their outermost layer is intensely warmed and chilled, the next layer is not nearly so affected. Instead of the rock being broken into fragments as with the frost wedge it is exfoliated, by the flaking off of its outer skin. Any projecting corners are attacked first and gradually convex surfaces are formed, ending in the production of great rounded boulders or even the dome-shaped hills known as inselberges.

Soils

One result of the weathering of rocks is the formation of soil, which consists of the products of chemical and physical weathering greatly modified by the action of plants and organisms and, in cultivated areas, by human activities. The study of soils has now become a science of its own, *Pedology*, but we may note here certain points.

Soils are usually stratified. The soil grades down through the subsoil, composed of partially weathered material, into the parent rock beneath. The soil itself usually shows a profile. The highest, or A horizon, is the zone of most intense weathering, from which much material has been leached out by solution. Much of this soluble material has been deposited in the underlying B horizon, whilst the subsoil is usually referred to as the C horizon. Sections in coniferous woodland growing on loose sands show these horizons very clearly. The A horizon has been leached to dazzling white sand whilst the B horizon is strongly ferruginous and often consists of a layer of hard iron pan.

Over the World as a whole, the type of soil profile is a function more of climate than of the parent rock. This applies particularly to areas in which there has been long continued weathering. Immature soils, more closely related to the parent rock, are to be found in those areas which were scoured by the ice-sheets of the last glacial period, so that the soil is the result of only a few thousand years of weathering and other changes.

Organic Weathering

Whilst the activities of organisms are mainly concentrated on soil formation, they can locally aid the breakdown of solid rocks.

Tree roots enlarge the cracks into which they penetrate and after the death of the tree, the rock may fall apart. Certain marine organisms can bore into rocks, either by the rasping action produced by the rotation of their shell or by the secretion of chemicals, which attack calcareous rocks. In this way the rocks are weakened and rendered more easily removable by other agents. Earthworms have the same effect, for their castings consist of finely divided material. Darwin calculated that the 150,000 earthworms in an area of average soil raise to the surface, ready for removal, as much as 10–15 tons of finely comminated material each year.

CHAPTER IV

Transportation of the Weathered Material

FOR denudation to continue, it is essential that the products of rock weathering be steadily removed, so that fresh rocks can be attacked. Otherwise the mantle of weathered material or 'regolith' will have a protective effect.

Gravity is one of the most effective agents of transportation. Loosened material is constantly moving downhill. On screes this is very apparent, for the material is lying at the angle of rest, usually between 25° and 35° and any disturbance, such as the fall of fresh blocks or someone walking on the scree, will at once set it in motion. Any heaped up unconsolidated material, whether composed of boulders or of sand grains, is kept in place by the internal friction between its particles and if this friction is reduced the particles must slide until they settle at a newer and flatter angle of rest. Excess water, either from heavy rains or from melting snow, is most effective in lubricating screes and often causes debris avalanches. In areas of high relief the momentum of the sliding screes is often sufficient to carry them right across valleys, damming up rivers and forming lakes.

Water percolating along the bedding planes of quite solid rocks can produce serious landslips. The necessary conditions are found where heavy well-jointed rocks rest on layers of clay, especially if the beds are dipping towards a cliff line or a cutting. After heavy rains the surface of the watertight clay becomes so lubricated that the rocks begin to slide across it. Often a great mass of clay subsides and moves along a curving slide plane to produce a rotational slip with the slipped mass dipping steeply inwards towards the cliff. Many examples of this are to be found round our coasts. The Undercliff between Ventnor and Blackgang in the Isle of Wight is

a jumbled mass of great blocks of chalk and sandstone which have slipped down from the cliffs above across the underlying clay, which is locally known as the 'blue slipper'. The last serious landslide in 1927 carried down with it a considerable length of road, which has not been repaired, for the possibility of further movement is so great especially as the sea is vigorously cutting into the toe of the slipped masses and making them more likely to move again.

The vibrations produced by earthquakes are another cause of avalanches and landslides, particularly in areas of high relief and slightly consolidated rocks.

But movement under gravity is not always rapid. Slow flowage or *Soil Creep* is very effective in transporting material downhill. This is due to other causes than the lubricating effect of water. For example, if the soil is baked by the sun and cracks the cracks will expand most on the downhill side, so that when the cracks close again on moistening, material will move downhill. A frost-shattered pebble will naturally fall downhill. A pebble may not be shattered, but may be heaved by the frost, owing to the formation of needles of ice below it. The needles will grow at right angles to the slope but when they thaw the pebble will settle vertically downwards and will have moved a fraction downhill. Soil creep is constantly at work and whilst its results are not spectacular great quantities of material are being slowly but steadily carried down the slopes into the valleys. The results of soil creep are shown by by the banking of soil on the uphill side of the obstacle formed by a hedge, by trees whose trunks have curved by the struggle to grow vertically or in quarries by beds which at depth are horizontal or even dip into the hill but which near the surface are bent over by *terminal curvature* and show an apparent dip downhill.

Rain not only lubricates the rocks but is very effective in washing down any loose particles. During heavy rain the minor irregularities of the surface over which it is streaming soon cause it to be concentrated into little gullies, the sides of which, if composed of loose material, will be constantly slipping so that the gullies are rapidly deepened. Rain falling on sand or clay containing large boulders can produce fantastic effects. Gullies form between the boulders and eventually the boulders will be left standing on little pinnacles or *earth pillars*. The boulder then acts as an umbrella, protecting the pillar, and as the surrounding material is washed away the pillars in effect grow higher and higher, until they may reach a height of as much as 70 feet. But as soon as the protective boulder

is blown off or otherwise dislodged the soft material of the pillar soon crumbles away.

The rain water may eventually find its way into a river. Rivers transport their load of sediment in one of four different ways. As already mentioned, many of the products of chemical weathering are soluble and form the *solution load*, which in some rivers is very considerable. The finest insoluble particles, of clay and silt, are carried along, owing to the turbulence of the water, as the *suspension load*, and if this is large the water appears dirty. Larger particles like sand grains are bounced along the river bed as the *saltation load*, whilst pebbles and boulders are dragged or rolled along the bed as the *traction load*. The proportion of the total load transported by any one of these methods is constantly varying, depending partly on the nature and size of the rockwaste which reaches the river but more particularly on the volume and velocity of the river. The transporting power of a river rises very rapidly with increase of velocity, probably by nearly the sixth power of the velocity, which means that if the velocity is doubled, the size of the boulders that can be moved is increased nearly 60 times. This explains why at times of little rain a river flows placidly between great boulders but, when the stream is in flood, these boulders can be heard grinding against each other as they are moved downstream. The total load carried by rivers is very great. It has been estimated that the Mississippi transports to the sea over 400,000,000 tons of rock waste per year and that the figure for all the chief rivers of the World combined is about 8,000,000,000 tons. Water in the form of *ice* can transport much bigger blocks than even the most violent floods but the movement is extremely slow, often only a few yards a year. Blocks, loosened by the frost wedge, fall on the surface of a glacier and become part of its load. Once imbedded in the ice they do not suffer the battering against each other of the material moved by a river. As a result, while the pebbles transported for a considerable distance by a river become rounded, those moved by ice retain their original angular shape though they are often scratched or striated by being ground against other blocks or against the rock wall of the glacier. One further point is that flowing water must always move its load downhill, ice also normally moves under gravity but where glaciers converge or ice-sheets are moving towards rising ground the pressure may be great enough for part of the ice to be driven uphill.

Wind can also be a very effective agent of transportation. The finest particles of clay grade size can be carried for very considerable

distances. In February 1903, falls of 'blood rain' were reported over large areas of southern England, the Low Countries and Germany. The rain had been discoloured by very fine reddish dust which had been blown into the atmosphere by severe sandstorms over the Sahara Desert. The larger particles of sand grain size are moved by saltation and rarely bounce more than a few feet off the ground. But the 'sand blast', concentrated just above the ground surface, can be very effective in scouring, grooving and polishing rock, or even metal, surfaces. Sand blast is not restricted to deserts, as anyone will realize who tries to walk bare-legged against a strong wind on a sandy beach.

If rain and wind attack a sandstone surface of irregular hardness they produce a coarsely pitted effect, known as *Honeycomb Weathering*; the weaker places having been scoured out, the more resistant standing out as low ridges.

In recent years the destructive effects of wind and rain in removing loose material have been tremendously accelerated in many parts of the World. Areas of unconsolidated rocks, without a vegetation cover, are being ripped very rapidly into gullies by rain storms and scoured by strong winds. The deep-cut valleys separated by sharp ridges composed of unstable sliding material form *badlands*, which are often extremely difficult to cross on foot. In the past badlands were restricted to semi-arid areas, mainly in the central United States, but within the last century their extent has been enormously increased by man's ill-advised activities. Forests have been felled, grassland ploughed up and then ruined by over-cultivation and as a result *soil erosion* is now a very serious menace over vast areas of China, the United States and Africa. A vegetation cover not only helps soil formation but by binding the soil particles together with its roots, and by the sheltering effect of its leaves, it greatly reduces the removal of material by rain and wind storms. But if the cover is stripped off, then the loose soil can be blown away and the whole country scoured down to the bed rock. As we have seen in the previous chapter weathering is a slow process and the formation of a fertile soil from bare rock, even with all modern aids, takes many years. Even if soil erosion can be stopped, and this is a difficult and costly matter, it will be a very long time before the affected areas can be properly cultivated again.

CHAPTER V

Work of Rivers

RIVERS show marked changes in character as they are followed from source to mouth. Near their head waters they are usually flowing rapidly in deep-cut valleys. The supply of coarse rock waste is large, rainfall is heavy over the hills and during the rather frequent floods the river is able to transport large boulders and stones and with these to abrade its bed. Irregularities in the hardness of the rocks over which it is flowing are etched out, the outcrops of the softer rocks forming the more placid reaches with rapids or waterfalls on the more resistant strata. Waterfalls occur where the beds are lying almost horizontally, rapids where they are dipping steeply. Waterfalls retreat upstream as the eddies in the pool below the fall wear away the soft rocks so that the hard bed, which produces the waterfall, is constantly giving way as it is undermined. The stream bed is abraded by the saltation and especially by the traction load of the river. Pot holes are formed where stones lodge against an obstruction and then are swirled round and round by the waters to wear out a circular depression. At times of low water numerous pot holes can often be seen with a number of well-rounded stones lying in them.

Valley Form

Rain wash and gravity slip are constantly attacking and wearing back the valley sides and except on the hardest rocks, where the river flows in gorges, are able to widen the valley more quickly than the stream is lowering its bed.

As one proceeds downstream the gradient of the valley lessens gradually, the velocity of the water decreases, though, owing to the entry of tributaries, the volume of water increases. Lessening

of velocity means very substantial decrease in the carrying and erosive power of the river and as a result whilst the total load carried may be greater its maximum size is smaller, whilst the valley sides slope less steeply. Finally one reaches a point at which the river begins to deposit part of its load. Instead of being completely V-shaped the valley now has a narrow flat floor, the *flood-plain*, formed of material which the river can carry only when it is in flood and which it must deposit as soon as the rush of water decreases. Alluvium, the material deposited on the flood-plain, consists of silt and clay with seams of sand and gravel. It is usually very fertile, for it is rich in chemicals, part of the solution load, and it also contains a considerable amount of organic material.

As the flood-plain widens downstream the river instead of following a fairly direct course usually begins to *meander* or swing from side to side of the flood-plain. The river is now flowing fairly slowly and is depositing a considerable part of its load. The meanders are not stable. As the river swings round a curve, it erodes and undercuts the bank on the convex side while it deposits part of its load in the slacker waters on the concave side of the curve. As a result the individual meanders of the meander belt move steadily downstream but not all at the same rate. If a particular meander is able to move faster than its predecessor, the river may be able to cut through the neck of the meander, forming a cut-off and converting the loop of the old meander into an oxbow lake.

Flooding

Serious flooding may occur over the flood-plain of a meandering river. In the headwater regions, where the gradient is steep and the velocity of flow high, the flood waters are confined within a narrow valley. They can move great boulders and tree trunks, which may form temporary dams and when these burst a flood wave is released to rush down the valley. But the danger of floods is known and habitations are usually built above the valley floor. As the valley widens and more tributaries enter the volume of flood water becomes greater, while the fertile flood-plain is usually highly cultivated so that flooding can do greater damage.

One method of flood protection is to attempt to confine the river within banks or levées. These are partly natural for when flooding does occur the rivers drop most of their load where the waters spread from the normal channel across the flood-plain. The natural levées are often artificially built up, until in an extreme case as in the Hwang Ho in China they may be nearly 100 feet

high and, owing to the silting of its channel, the river bed may be above the level of the flood-plain. Bursting of the banks under such conditions will produce the most serious floods. Up till 1853 the Hwang Ho River flowed into the Yellow Sea but in that year the river burst its banks, took a new course and since then its mouth has been in the Gulf of Pohai, 200 miles to the north of its previous position.

Another river very subject to flooding is the Mississippi, which has a very wide flood-plain in its lower reaches. Artificial levées were first built near New Orleans in 1717 and were steadily added to, until by 1932 there were 2500 miles of levées with an average height of 13 feet. But the levées had not prevented a number of disastrous floods so, in this year, the method of *flood control* was changed. The new policy was to avoid flooding by taking the waters down to the sea as quickly as possible. The course of the river was shortened by making artificial cut-offs through the necks of large meanders; 12 such cut-offs shortening the course of the river by 116 miles in a previous length of 330 miles. At the same time reservoirs were constructed in the tributaries so that their floods could be held back and discharged into the main river only after the peak of its flood had passed. The silt load of the river was reduced by a campaign of strengthening and protecting its easily eroded banks and by afforestation of the headwater region. This new policy certainly seems to be successful for floods, though not completely prevented, have been much less serious.

The deposition of load can cause much trouble in navigable rivers. The policy then is to build retaining walls and solid piers to concentrate the flow of the water into one fairly narrow channel, which will be kept at the desired depth by the scour of the water, though a certain amount of dredging may be needed as well.

Longitudinal Profile

The longitudinal profile or *thalweg* of a river is constructed by determining the height above sea-level of the water surface at as many points as possible. When these points are plotted the correct distance apart they will be found to lie on or very near to an assymptotic curve, concave upwards, with a steep upper and a nearly horizontal lower portion (Fig. V, 1).

A river can be regarded as attempting to reach the *state of grade* simultaneously all along its course. If the river is perfectly graded, its energy derived from the volume and velocity of its flow is everywhere just sufficient to transport its load. Variation in any of these

three variables, volume, velocity and load, must upset the balance. If the energy of the river is anywhere insufficient, then it must aggrade by depositing part of its load. If there is an excess of energy, then it must use this in degrading or eroding its bed. A river is normally degrading in its upper and aggrading in its lower reaches, but this may not be the case over shorter distances. The concept of a graded river is therefore an ideal, to which a river is always approaching but never attaining except for short periods of time along a part of its course. It is however of great value in explaining the effect on a river of change of sea-level, the base-level to which its profile must be graded.

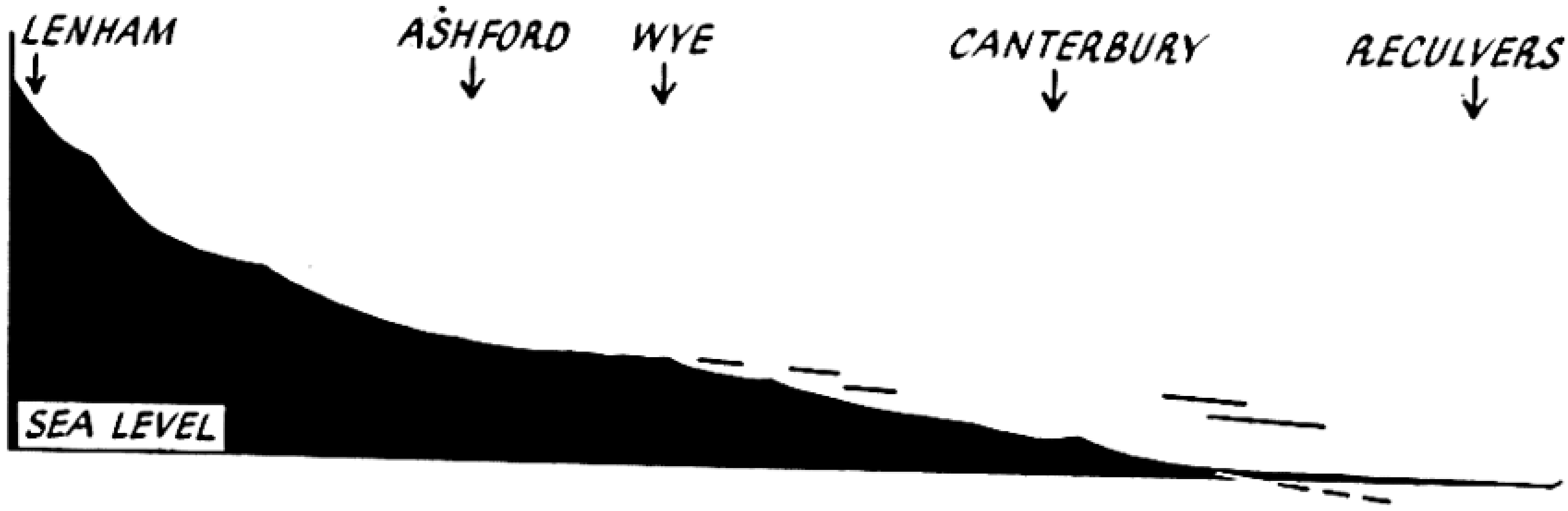


Fig. V, 1.—Longitudinal Profile (Thalweg) of the River Great Stour in Kent

Five heads of rejuvenation are shown, whilst the lowest graded reach is extended for a short distance below the 'fill' of the Buried Channel. The short lines above the profile are fragments of terraces. Note that the flood-plain for a considerable distance above Wye is graded to the higher terrace.

If there is a *negative* movement or fall in sea-level, the lowest part of the profile will be out of grade. A wave of downcutting will move upstream as the river adjusts itself to the new (lower) sea-level. Theoretically a gorge will be cut through the old flood-plain, which will be left as a pair of sand or gravel *terraces* on either side of the new flood-plain. Rainwash and gravity slip in the unconsolidated deposits will soon smooth the sharp edges of the gorge and the new flood-plain will be bounded by bluffs beyond which extend the flat surfaces of the terraces.

The river is said to be *rejuvenated* by this negative movement, for it has begun active erosion in areas where it was previously aggrading. The wave of rejuvenation or of downcutting will proceed steadily upstream and the point to which it has reached will be marked by a *knick point* or head of rejuvenation below which

there is a steepening of gradient (Fig. V, 1). In rivers flowing over soft strata the change of gradient may be so slight that it can only be detected by levelling, but on harder rocks it will probably be marked by a waterfall, where a particularly resistant band has halted the upstream movement of one or more waves of back-cutting.

A rise or *positive* movement of sea-level will submerge that part of the valley near the mouth. Aggradation will start and the drowned part of the valley may soon be silted up. Aggraded valleys of this type can be recognized by the sharp change of slope at the back of the flood-plain. The sides of a valley are normally graded to the valley floor and merge gently into the back of the flood-plain or river terraces. But in a drowned valley, the valley sides are graded to a lower level than the new flood-plain and therefore plunge steeply beneath it.

The Terraces of the River Thames

Many rivers show evidence of both positive and negative movements of sea-level. For example, the Thames is bounded near London by fragments of three distinct terraces laid down at times when sea-level was 100 feet, 50 feet and a few feet higher than at present (*see* Fig. V, 2). There are only isolated patches of the oldest (the highest) Boyn Hill Terrace, for it has been greatly dissected by the tributaries of the Thames, but the middle or Taplow and the lowest or Flood-Plain Terraces are much more complete and even in the densely built up areas of central London the bluffs separating the flat terrace surfaces can be easily recognized (Fig. V, 3). Clapham Common Station is an excellent viewpoint for seeing the bluff separating the Boyn Hill Terrace of Clapham Common from the Flood-Plain Terrace of Battersea Park, whilst on the other side of the Thames, the bluff between the Taplow and Flood-Plain Terraces can be traced from Exhibition Road with its museums, past Hyde Park Corner and Constitution Hill to the steep rise of St. James's Street and the streets on the north side of the Strand and so to Holborn Viaduct spanning the valley cut through the terrace by the River Fleet, now flowing in a culvert. The construction of bridges across and tunnels beneath the Thames has been made difficult by the existence of a buried channel, cut to a depth of 60–70 feet below sea-level. A rapid rise of sea-level within the last few thousand years caused aggradation and the Buried Channel is now infilled with waterlogged lenses of sand and gravel, with layers of peat and tree trunks, indicating brief periods

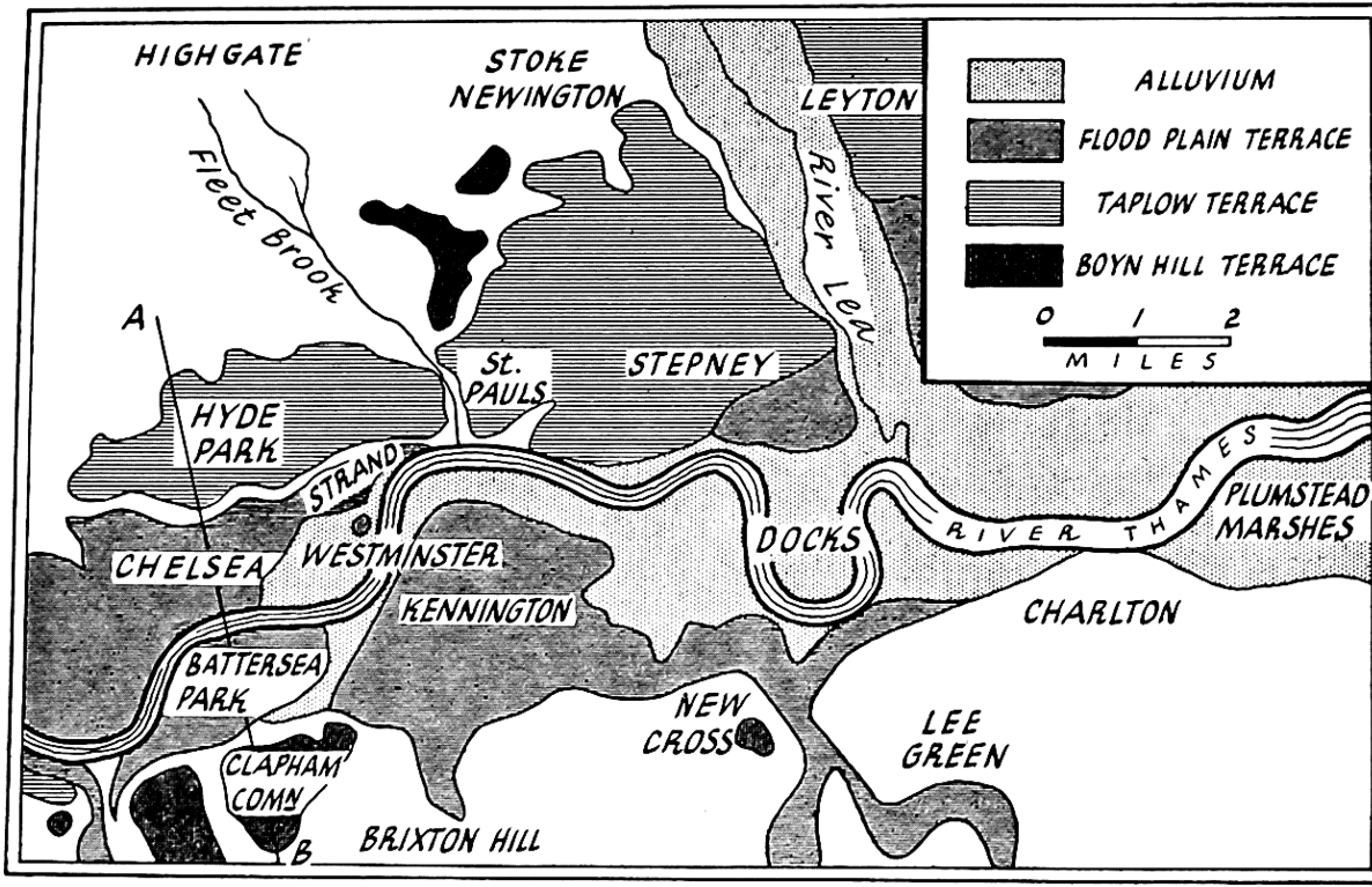


Fig. V, 2.—Map (after H.M. Geological Survey) of the Deposits of the River Thames Around Central London

London Clay and other 'solid' rocks are left white.

when woods grew on the flood-plain. The foundations of the bridges have to be driven through these variable and weak deposits into the compact London Clay beneath, whilst special precautions have to be taken against inrush of water when driving tunnels through the fill of the Buried Channel.

The deposits laid down by the Thames in the London area therefore record a fall of sea-level of at least 170 feet, a fall that was interrupted by three periods of 'still-stand', when the three main terraces of the Thames, each graded to a sea-level which must have been stationary for a long period, were formed. Since the low sea-level marked by the base of the Buried Channel, there has been

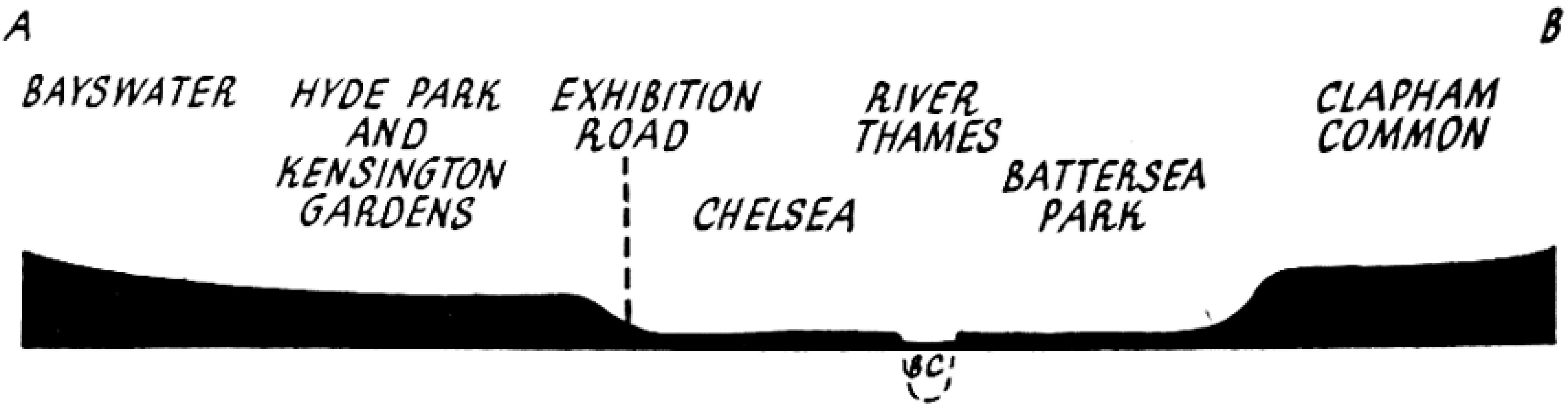


Fig. V, 3.—Sketch Profile from A to B on Fig. V, 2, Showing Terraces and Bluffs

B.C. indicates the approximate position of the Buried Channel extending well below sea-level.

a positive movement of about 70 feet and now the river, where it is not too embanked, is laying down alluvial deposits which may in the future, after a new negative movement, add yet another tread to this flight or staircase of terraces.

The Buried Channel of the Thames can be traced upstream to Brentford in Middlesex where there must be a head of rejuvenation, but this is hidden beneath the alluvial deposits. The terraces rise gradually upstream and near Slough, 20 miles to the west of London, the Boyn Hill Terrace is at 175 feet, the Taplow at 100 feet and the Flood-Plain Terrace at 65 feet above sea-level. River terraces always have a marked longitudinal slope and therefore should be named after some locality where they have been studied, rather than called the 100 Foot, 50 Foot Terrace, etc., for the terraces are only at this particular height above sea-level or the present flood-plain for a limited distance. If a terrace can be traced far enough it will be found to approach nearer and nearer to the flood-plain as it rises. Finally the terrace will merge into the flood-plain at a

head of rejuvenation but will disappear at the next head of rejuvenation, for above this the flood-plain is graded to a still higher and older base-level (*see* Fig. V, 1).

Drainage Development in Scarplands

If an area, with parallel bands of alternating hard and soft rocks outcropping across it, is uplifted so that the land surface is sloping in the same direction as, but at a lower angle than, the dip of the beds, streams will begin to flow down this slope. These streams are known as *consequents*, for their direction is consequent on the uplift. They will begin to cut out valleys of the type described above. These valleys will be widened most rapidly along the strike of the softer beds. Streams known as *subsequents* will begin to flow down the sides of the valleys at right angles to the direction of the consequents and by headward erosion will begin to extend backwards along the strike of the softer rocks. A landscape of very typical form will be etched out of what was originally a tilted plain. The more resistant strata will form lines of hills (*cuestas* or *escarpments*) with a steep scarp face facing up or against the dip of the rocks and a gentle dip slope parallel to the dip. The various cuestas will be separated by the *strike vales* eroded by the subsequent streams. The drainage will now be markedly rectangular in pattern for the subsequent streams will have been joined by *obsequent* streams, rising at the foot of the scarp's slopes and flowing against the dip of the rocks and by *secondary consequent* streams trenching the dip slopes (Fig. V, 4).

Typical scarplands of this type are well developed in southern England, the Chiltern Hills, the Marlborough Downs, the North Downs, etc., being cuestas with the Vales of Aylesbury, the White Horse and Holmesdale at their feet.

River Capture

Differences of rainfall or of spring action in the headwater regions or slight differences in the hardness of the rocks crossed will enable one of the consequent streams to downcut more rapidly than its neighbours. As all parts of a river system are graded to one another, its strike vales will also be lowered rapidly and its subsequents will therefore push back by headward erosion the divides separating them from the subsequent tributaries of neighbouring river systems. Eventually one of the subsequents may extend back far enough to reach a neighbouring consequent river and as it is at a lower level the waters of the consequent will be diverted down

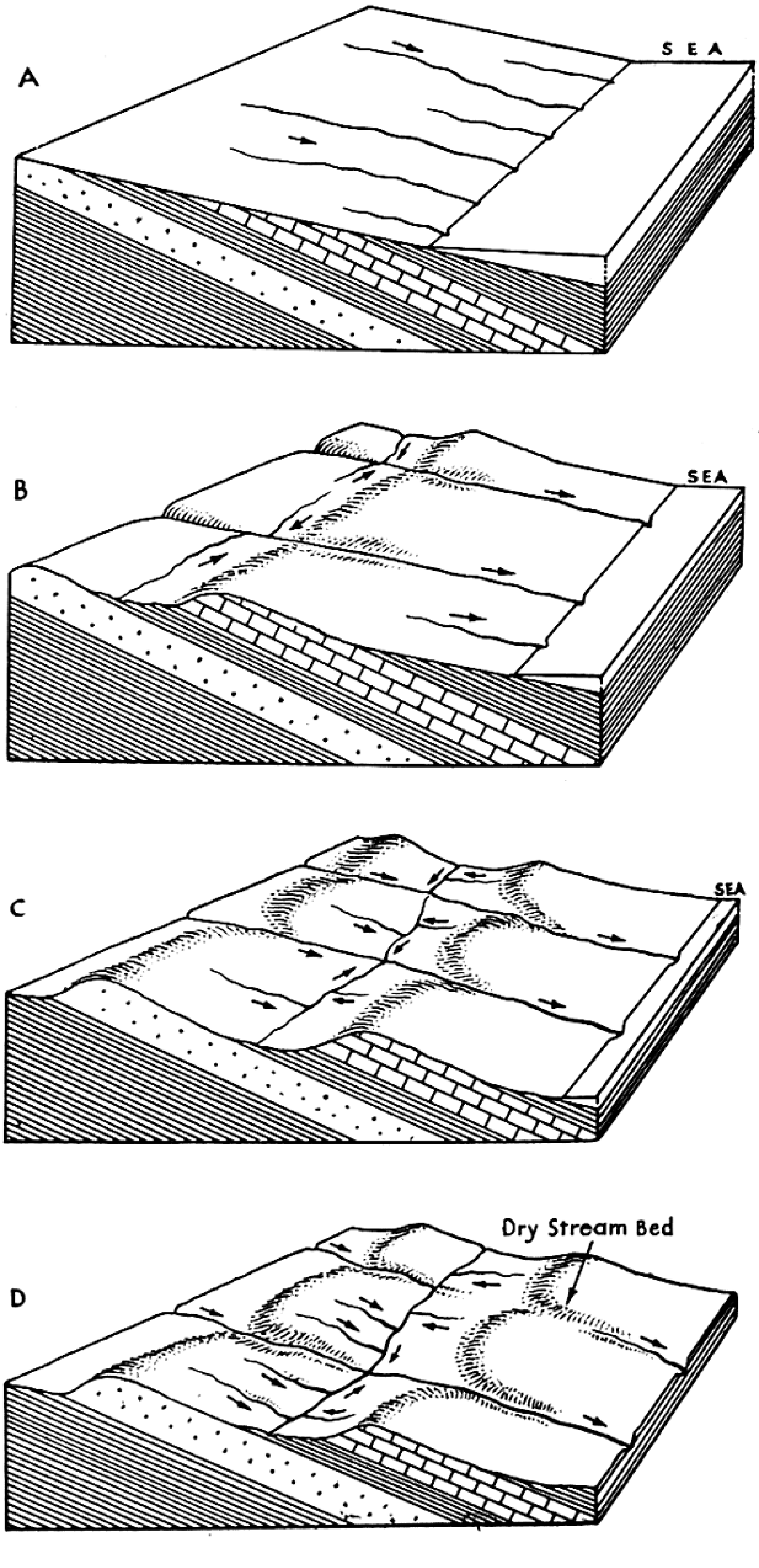


Fig. V, 4.—Drainage Development in Scarplands

A. Initial consequent drainage.
B. Etching out strike vales by subsequents.
C. A subsequent tributary from the nearer consequent is just capturing the other consequent river.
D. Typical scarpland topography with a wind gap and a misfit stream marking the line of the captured consequent.

Note the recession of the escarpments down dip.

the subsequent and so into the more rapidly downcutting 'master' consequent. The successful subsequent is said to have captured the consequent, the place of capture being marked by a right-angle bend or *elbow of capture*. The downstream portion of the former valley of the captured consequent will be shown by wind gaps in the cuestas with 'misfit' streams, far too small to have cut the valleys in which they are flowing, draining down the dip slopes and occupying the lower portions of the valleys below the wind gaps.

Numerous cases of river capture can be studied in the scarplands of England. On Fig. V, 5, are shown two cases. A subsequent tributary of the Wey, cutting back to the south of the Hog's Back, has succeeded in capturing near Farnham a stream which rises near Alton and had cut, before it was captured, a gap across the North Downs to flow northwards to join the Thames near Reading. The wind gap in which Farnham is built with an elbow of capture to the south and the misfit River Blackwater to the north make this a classic example of river capture. But the River Wey has been attacked in its turn in the southern part of its drainage basin by the River Arun, which has a shorter and therefore steeper course to the sea. The Bramley branch of the Wey is a misfit and whilst the features of the capture are not so clearly visible, there can be no question that the former tributaries of the Bramley Wey rising in the high ground of Hindhead have been captured by the Arun system and diverted southwards to the English Channel. In the country around Alfold there is a marked contrast between the valleys occupied by the tributaries of the Wey and of the Arun. Those of the Wey have wide flat floors with the streams flowing at the surface, but the headwaters of the Arun, although this is a country of soft clay usually forming very gentle slopes, have cut steep-sided gorges, 20 or more feet below the surrounding countryside. They are vigorously downcutting or incising themselves and also are pushing the Wey-Arun watershed steadily northwards. In time, further cases of capture must occur for the divides are obeying what is often called the *Law of Unequal Slopes* and are steadily, though imperceptibly, moving down the side of gentler gradient.

Drainage Development on Folded Rocks

The initial drainage pattern will be rectangular with the initial consequent streams flowing down the synclinal axes and secondary consequent streams draining down the slopes of the anticlinal ridges between the valleys. The initial consequent streams are *longitudinal* for they flow along the strike, whilst the secondary

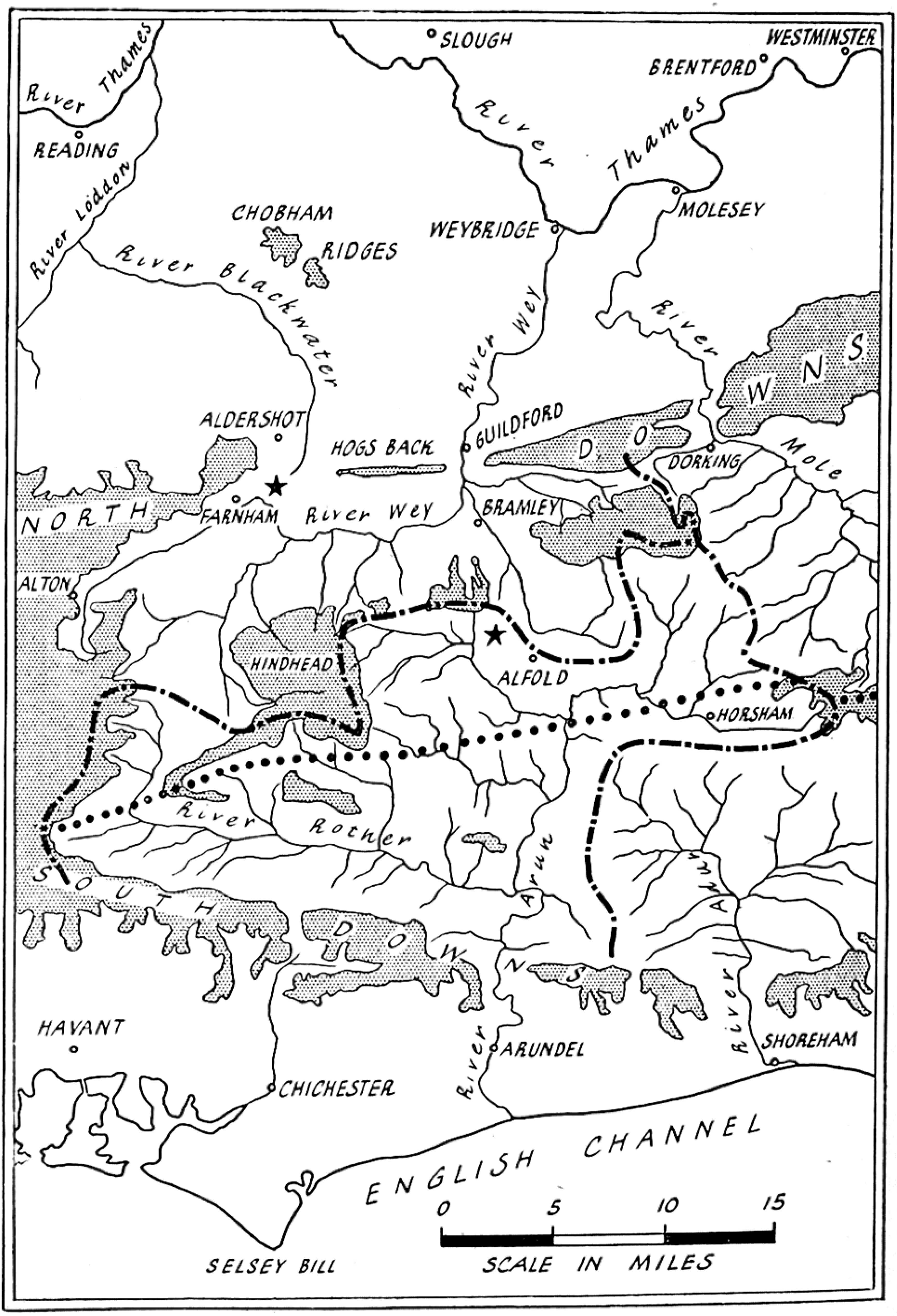


Fig. V, 5.—Drainage Map of the Western Part of the Weald
The broken heavy line marks the present watershed of the Arun-Rother system, the line of circles its original position before the capture of the headwaters of the Wey system. Stars indicate the cases of river capture referred to in the text. Areas more than 400 feet above sea-level are stippled, showing the position of the cuestas and strike vales and the relation of the various streams to them. Note the drowned coast line to the west of Chichester and the eastward deflection of the mouths of the Rivers Arun and Adur.

consequent streams down the ridges are *transverse* to the strike and in this respect resemble the initial consequent rivers of scarplands. The longitudinal consequents flowing along the pitch of the folds will be more sluggish than the transverse consequents. Erosion and valley widening will therefore proceed more rapidly on the ridges, especially if a closely-spaced joint system has been developed by the up-arching of the strata. This will greatly facilitate the breaching of any resistant rock capping the anticlines and once a stream has cut through this into softer strata beneath, it will rapidly widen its valley into an *anticlinal vale*, surrounded by scarps retreating, owing to the headward erosion of subsequent streams, down the flanks of the folds.

But a folded area of rocks is not like a sheet of corrugated iron with the ridges all parallel and their axes all horizontal. It resembles much more a rucked-up sheet with the folds roughly parallel but overlapping each other *en échelon* whilst each fold is fairly short and pitches steeply at its ends.

The crest lines of some of the folds will be higher than others. These are the folds that are most likely to be breached first, for the streams flowing down their flanks will have a steeper gradient and greater erosive power. Therefore, as in scarplands, certain subsequents will be more successful than others and will capture the drainage of neighbouring anticlinal vales. Eventually longitudinal subsequent streams will develop along the axes of the anticlines. These streams, particularly if they are now flowing on soft rocks, will be able to lower their valleys to below the level of the longitudinal consequent streams, which may not even have succeeded in breaching the cap rock. Obsequent tributaries of the successful subsequents will capture parts of the longitudinal consequents and so gradually the drainage of the area will be concentrated along the line of the anticlinal valleys (Fig. V, 6).

This means that the *relief* of the area will be *inverted*, for it is now the inverse of the geological structure. Originally the relief was uninverted, the valleys being synclinal and the ridges anticlinal in structure. But now the valleys are anticlinal and the ridges synclinal.

We have considered the simplest case with a resistant cap rock overlying softer beds. But igneous rocks are often intruded along the axes of anticlines or there may be an alternation of hard and soft layers. Therefore whilst inversion of relief is frequently developed in areas of folded rocks, this is not a general rule, for the rate at which the anticlinal areas can be worn away compared with the

synclinal areas is obviously very dependent on the nature of the rocks.

The Cycle of Erosion

We clearly cannot regard a landscape as static. It is always in the process of change, though the process may be so slow as not to be apparent by ordinary human standards. The great American

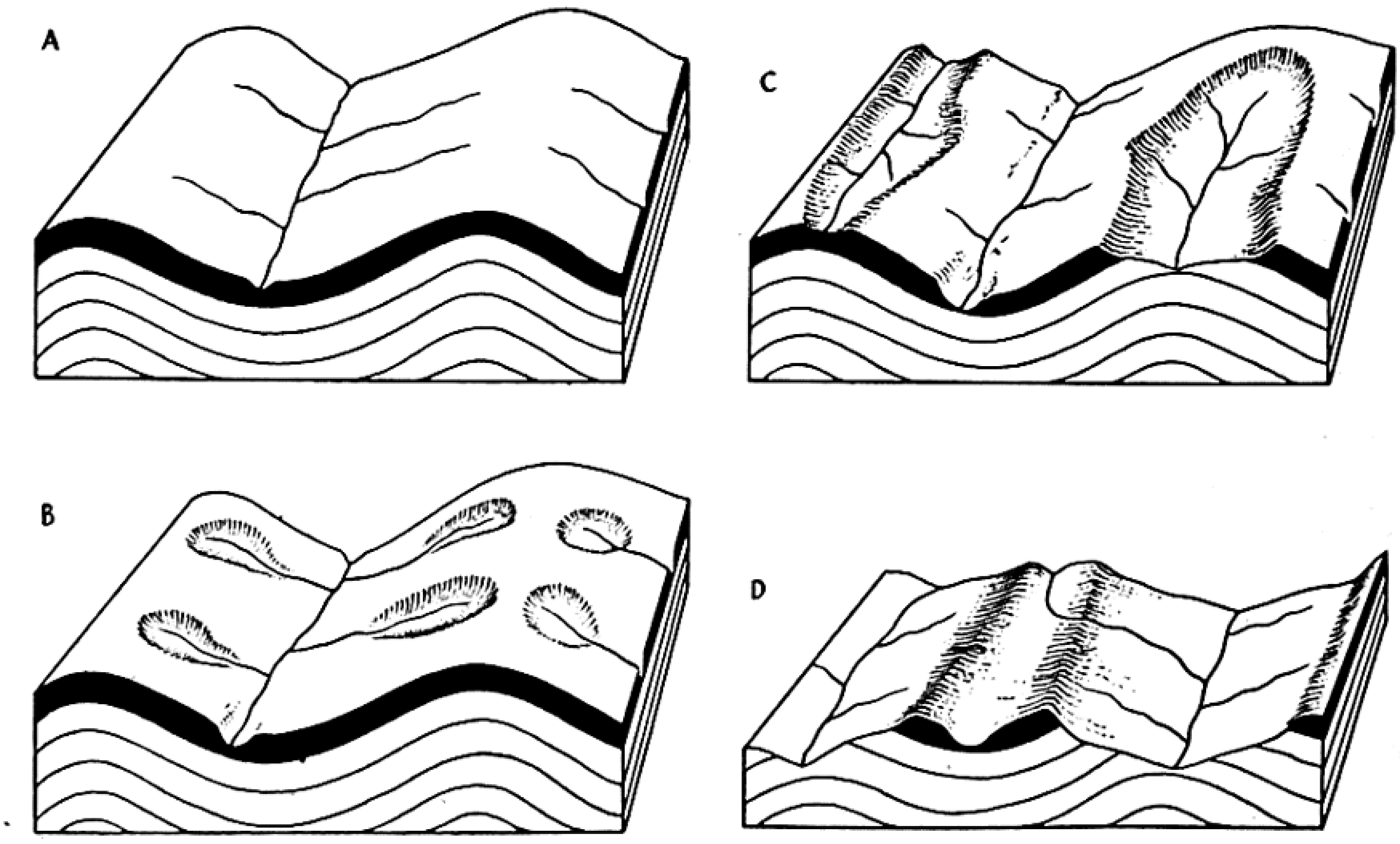


Fig. V, 6.—Drainage Development on Folded Rocks

A. Initial consequent drainage.
B. First stage in the development of anticlinal vales.
C. Subsequent drainage along the anticlinal vales.
D. Relief is now inverted and the initial consequents have been captured by the subsequent streams.

physiographer W. M. Davis crystallized the ever-changing nature of landscapes in his concept of the Cycle of Erosion. An uplifted land surface with numerous and closely spaced consequent streams trenching the original constructional slope he regarded as in the state of Youth. With the passage of time, the drainage became more rectangular in plan, capture reduced the number of consequents, whilst the valleys were widened. The widening of the valleys would steadily reduce the width of the interfluves and finally the last traces of the constructional surface would disappear and Maturity would have been reached. As the interfluves were then lowered more rapidly than the valleys were deepened, the

relief of the area would be reduced and gradually the landscape would pass into the state of Old Age with meandering rivers flowing quietly through wide valleys with gently sloping sides. Finally the land would be worn down to an almost level surface or *peneplain* with isolated hills or *monadnocks* rising above it, due to the presence of particularly resistant rocks.

The value of Davis's concept is twofold. He has provided both a picture of the sequence of changes produced by erosion and also a terminology to describe concisely the stage in this sequence reached by any landscape. The processes he regarded as responsible for the retreat of slopes, etc., have been strongly criticized but his main concept, on which the Science of Geomorphology is based, remains. He regarded a landscape as explicable in terms of Structure, Process and Stage. Structure to him included not only the geological structure of the rocks but also their physical characters, i.e. 'a uniformly dipping series of alternating hard limestones and soft clays' as distinct from 'isoclinally folded slates of uniform character cut by resistant dykes and small bosses of hard granite'. Process, the method of erosion, whether normal (rain and rivers), glacial, aeolian or marine, or some combination of these. Stage, that reached in the cycle of erosion.

Superimposed Drainage

A rectangular drainage system is usually well adjusted to the structure of the rocks, in the sense that there are valleys along the outcrop of the softer beds and the rivers cut more or less straight across the hills formed by the harder rocks. But in the north and west of the British Isles the drainage is often not rectangular and is clearly not adjusted to structure, for the same river may cross the outcrop of a particularly hard band two or three times whilst there is no obvious structural reason for the position of the valleys. The drainage must have developed on rocks separated by a plane of unconformity from those on which it is now flowing. The original drainage plan would have been determined by the nature and variations of hardness of the younger series, but when the rivers cut down through the plane of unconformity, they reached an entirely different group of rocks, to whose structure their plan was unrelated.

The Lake District rivers are a classic case of superimposition. The strike of the old steeply dipping rocks of the central parts is north-east to south-west, but as shown in Fig. V, 7, the drainage of the area is radial and only a few minor valleys are along the

strike. The Lake District is encircled, except where it is breached by the sea, by a cuesta formed of limestone dipping gently outwards and resting unconformably on the older strata. Originally this lime-

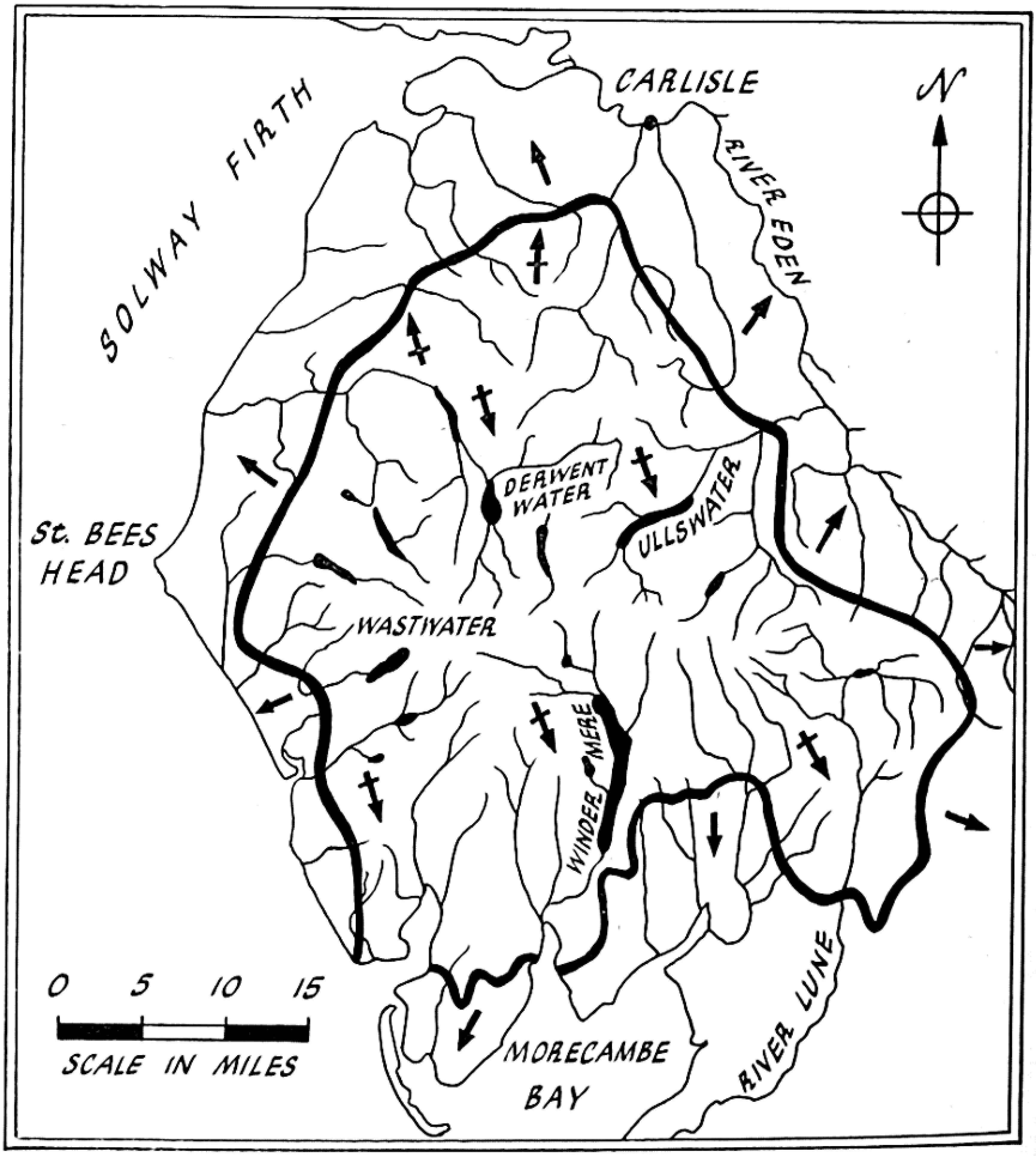


Fig. V, 7.—Superimposed Drainage of the Lake District
The heavy line marks the unconformable boundary between the younger and older groups of rocks. The direction of dip in the former is shown by the plain arrows and in the latter by the arrows with a cross bar.

stone must have extended right over the Lake District. The radial drainage must have developed when the limestone and any beds resting conformably upon it were arched up into a dome. Long continued erosion has stripped the limestone off the centre of the

dome and its scarp edge has retreated far down the flanks of the dome. The rivers with very little change of course have incised themselves deeply into the older rocks to whose structure they have only just begun to adjust themselves.

In this case both groups of rocks are present and their unconformable relationship can be seen in many exposures but there are many cases of superimposed drainage, where all trace of the younger strata has been removed; their former presence is however shown by the lack of adjustment of the drainage to the structure of the rocks on which it is now flowing.

Antecedent Drainage

So far we have not considered the effect of uplift of part of the area across which a river is flowing. If the uplift is sufficiently rapid the river will be diverted to flow parallel to the folds. But there is the possibility that the river may be able to maintain its course by downcutting as the land rises. The Brahmaputra is a probable example of antecedent drainage. Rising in the Tibetan Plateau it flows eastwards parallel to the Himalayan chains for nearly 1000 miles and then turns southwards to cut through the mountains in some of the deepest gorges on Earth to reach the Bay of Bengal. We know that the folding and uplift of the Himalayas occurred, geologically speaking, very recently and indeed it is probable that uplift has not completely finished. It is extremely difficult to explain the course of the Brahmaputra unless it is older than the Himalayas and has succeeded in maintaining its course across them, despite an uplift of many thousands of feet.

Karst Topography

Land forms very different from those described above are to be found in certain areas underlain by thick beds of limestone. There is little or no surface drainage, for the rainfall disappears down swallow holes and gaping joint planes to feed underground rivers. The roofs of caves and river channels often collapse owing to the solution of the limestone and so very distinctive topography is produced, named after the Karst lands of Yugoslavia on the eastern side of the Adriatic Sea. This is the type area from which have come the names for the different features, but typical Karst topography is also developed in parts of the West Indies, in Kentucky and Florida in the United States and in small areas of the Pennines in northern England.

A Karst cycle of erosion has been recognized (Fig. V, 8), commencing with the exposure of the surface of the limestone by the stripping of the cover of younger rocks. Solution of the limestone produces clints and swallow holes (*dolinas* in Yugoslavia) down which the existing surface drainage begins to disappear. The dolinas steadily grow in size and eventually a number of them may unite to form a large depression or *uvala*, aided perhaps by collapse of the roofs of caves. Maturity is reached when all the drainage is underground. As solution continues to lower the ground surface, conical hills or *hums* will develop between the steadily widening dolinas and uvalas. Eventually the surface will have been lowered enough to approach an insoluble bed underlying the limestone. Old Age will be marked by the reappearance of surface drainage as the rivers cut down to this bed. These rivers will be separated by more or less level surfaces of barren limestone with low hums rising above it as do monadnocks above the peneplain produced in Old Age by normal (fluviatile) erosion.

The Dry Valleys of Chalk Downland

Innumerable valleys occur in the Chalk areas of south-eastern England and northern France; valleys of a characteristic appearance with their sides sweeping in gentle curves to a valley bottom, which is usually dry and without any stream in it. But the form and plan of these dry valleys shows that they must have been cut originally by flowing water.

The Chalk is rather a soft type of limestone traversed particularly near the surface by closely spaced joints. Rain falling on the Downs percolates down these joints, dissolving away some of the Chalk, until it reaches the 'water-table', the level below which all the fissures in the Chalk are filled with water. The water-table is usually well below the surface of the Downs but some of the valleys are sufficiently deep to reach it and these contain flowing streams. On Fig. V, 5, the valleys of the rivers Arun and Adur cut through the Chalk cuesta of the South Downs, whilst the shape of the 400-foot contour line indicates the many dry valleys trenching the dip slope.

The origin of these dry valleys is rather complex. According to one view they are a legacy from the last glacial period. The main ice-sheets did not extend as far south as the North and South Downs, but there must have been snow-caps on the higher hills, whilst the Chalk must have been frozen to a considerable depth. Rain water and melt water from the thawing snow caps, therefore, could not

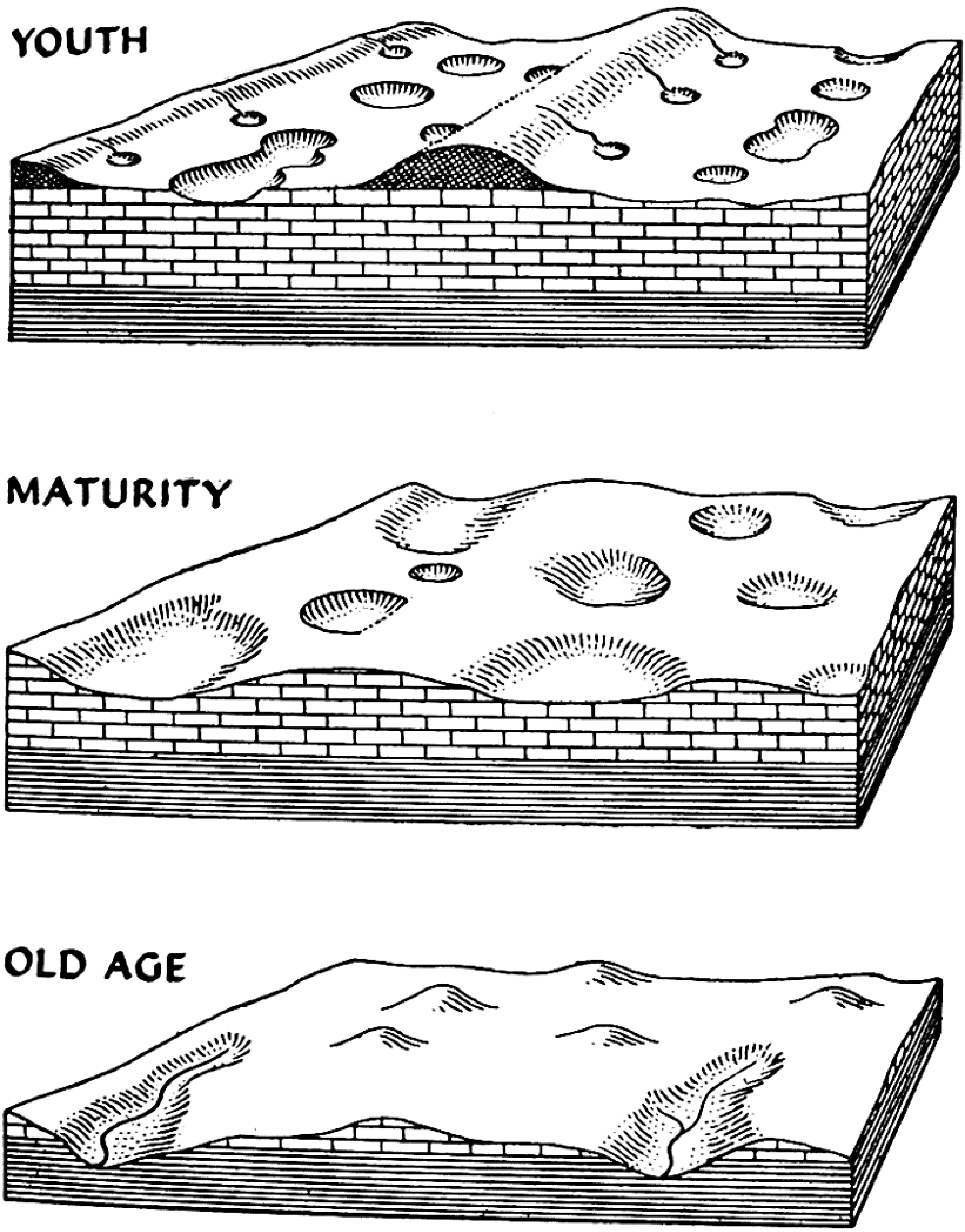


Fig. V, 8.—The Karst Cycle of Erosion

Youth: The limestone is being exposed by the removal of an overlying insoluble bed. Streams flowing off the ridges formed by this bed disappear down dolinas when the limestone is reached. The larger depressions are uvalas.

Maturity: All drainage is underground and the surface of the limestone is pitted with dolinas and uvalas.

Old Age: The limestone has been almost completely dissolved away. Streams are reappearing where the underlying insoluble stratum has been reached. Low hums rise above the almost level surface of the limestone.

penetrate downwards through the ice-filled joints but must have eroded valleys as it flowed over the surface. But the cuestas formed by the resistant Chalk have not always been in their present position. Erosion causes all escarpments to recede slowly down the dip. Outlying hills such as Bredon Hill near Cheltenham, standing some miles to the west of the scarp face of the Cotswold Hills, are relics left behind by a retreating escarpment. Near Limpsfield on the Kent-Surrey border are patches of a distinctive gravel which must have been formed at the foot of a scarp slope but are now nearly two miles from the scarp face of the North Downs. It is only the upper parts of the Chalk valleys that are dry, for springs, many of them 'bourne' springs (p. 284), break out far down the dip slope, showing that the lower parts of the valleys have cut down to the

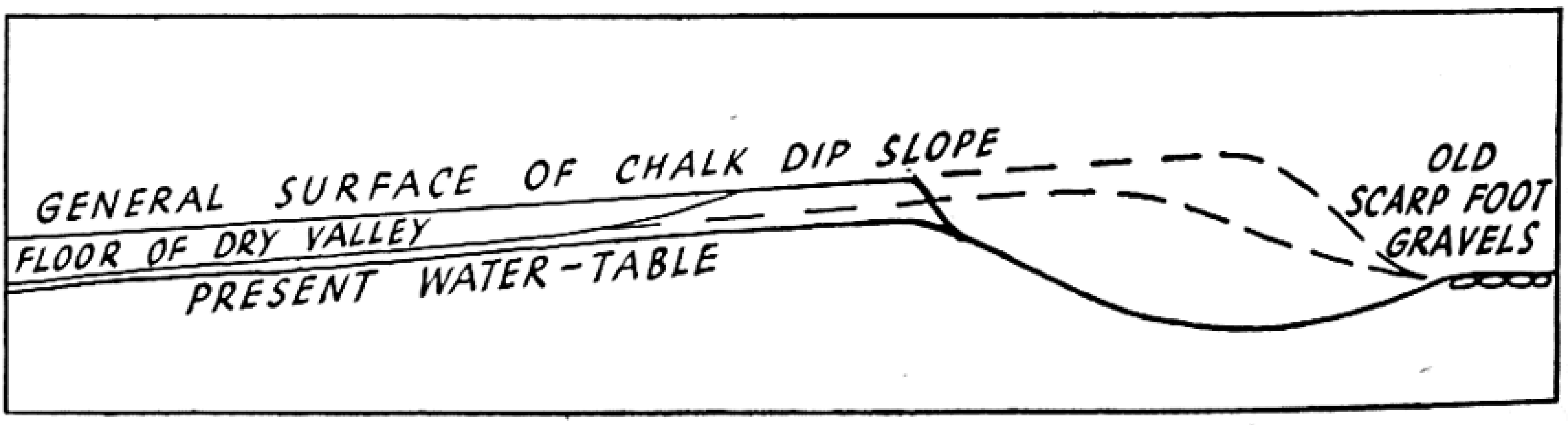


Fig. V, 9.—Scarp Recession and the Formation of Dry Valleys (after Fagg)

The present topography is in firm lines. The dotted lines show the position of the scarp and of the water-table, when the gravels were deposited at its foot. Streams rising from springs were then able to cut valleys down the dip slope, but as the scarp has receded the water-table has dropped and these valleys are now dry.

water-table. When the scarp face was standing some miles further up dip, the height of the water-table in these valleys must have been correspondingly higher (Fig. V, 9).

We must therefore regard the dry valleys, so typical of Chalk areas, as cut originally by streams at a time when the water-table was standing at a much higher level than at present. The drop in the water-table is due to scarp recession aided perhaps, though the evidence is not nearly so conclusive, by a decrease in rainfall. The cutting of these valleys must have been greatly accelerated during the glacial period by water flowing over the surface of the frozen Chalk and indeed certain of the dry valleys, such as the Devil's Dyke trenching deeply into the scarp face of the South Downs near Brighton, resemble very closely the valleys cut by melt waters in the glaciated areas described in the next chapter.

CHAPTER VI

Glaciation

THE snow line, the level above which snow and ice persist throughout the year, slopes from about 16,000 feet above sea-level at the Equator, to about 9000 feet in the Alps, passes just above the top of the highest mountains of the British Isles and reaches sea-level in roughly latitude 80°. Snow is compacted by the weight of later falls from flakes into loose granular névé and finally into hard ice, composed of interlocking crystals. By the sliding of crystals on one another, ice can move slowly, flowing either downhill under gravity or if the pressure is great enough it can move uphill. Rivers of ice or *glaciers* spread from the areas of accumulation down the valleys to well below the snow line, and if they reach the sea or other bodies of water form floating ice-sheets from which masses break off as icebergs.

A distinction is usually made between the great or continental ice-caps, thousands of square miles in area, restricted to high latitudes and the valley glaciers found in any latitude on mountains rising above the snow line. But the two really merge into one another, as can be seen in the valley glaciers spreading down from the Greenland ice-cap. In places, such as Alaska, a number of valley glaciers unite on the lower ground at the foot of the mountains to form piedmont ice-sheets.

Valley Glaciers

Valley glaciers afford today the easiest means of studying the work of ice in eroding the rocks over which it moves, in transporting the debris and in finally depositing this where the ice melts. But it must be remembered that during the glacial episodes of the last million years, a large part of the Northern Hemisphere was covered

by ice-caps of truly continental size (Fig. VI, 1), so that it is necessary to study both the existing shrunken remnants of these ice-caps as well as piedmont and valley glaciers before all the land-forms found in the areas glaciated during the maximum extent of the ice can be adequately explained.

As a glacier moves down its valley at a rate measurable in yards per year, the ice becomes loaded with debris, consisting partly of material which has fallen from the valley walls as a result of the 'frost wedge' and partly of fragments which have been 'plucked'

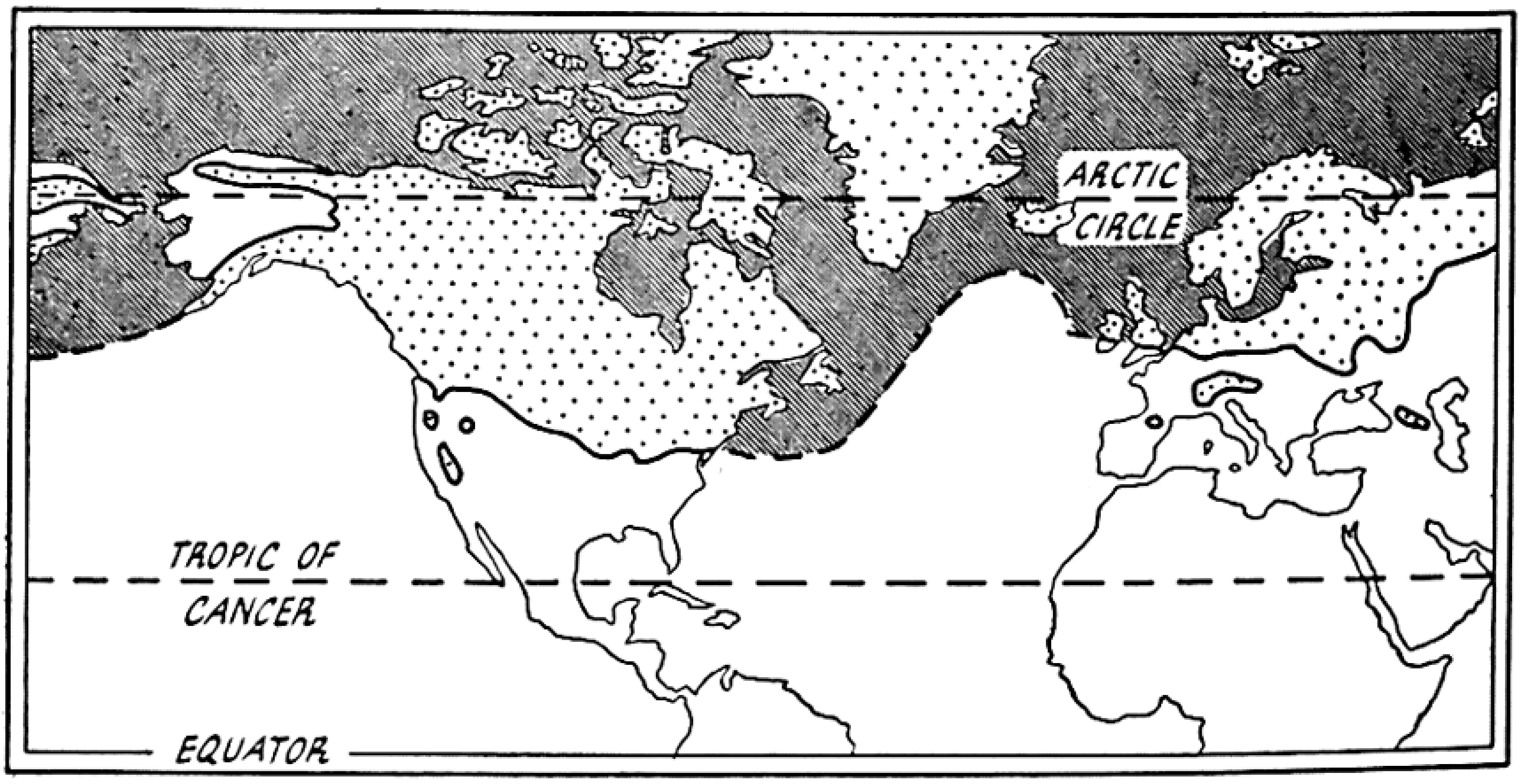


Fig. VI, 1.—Probable Extent of the Ice-Sheets at the Maximum of Glaciation (after Flint)

Glaciated land areas are coarse-stippled and the probable areas of floating ice fine-stippled. Only the largest of the glaciated mountain areas (Alps, Carpathians, Pyrenees, Rockies, etc.), south of the main ice margin are shown.

from the sides and bed of the glacier by being frozen into the moving ice. The material which falls on to the glacier is thickest on its sides and gradually builds up mounds of *lateral moraine*. The subglacial material carried along in the lower levels of the glacier is added to by that part of the terminal and median moraines, which falls down the crevasses or large cracks, which sometimes seam the surface of a glacier. Near the snout or end of the glacier the ice may be heavily charged with transported material or be strongly banded with layers of clear and dirty ice. The load carried by the glacier is deposited where the ice melts to form a roughly crescentic mound or *terminal moraine*; crescentic because the ice moves faster in the centre of the glacier.

Moraines are composed of completely unsorted fragments of rock, often angular and varying in size from the largest boulders downwards. The boulders are fresh and unweathered and often show grooves or striations, caused by grinding against the sides and floor of the valley or against other fragments frozen in the ice. Subglacial streams, issuing from beneath the ice, seep and cut their way through the terminal moraine. They often appear quite milky owing to the large amount of 'rock flour', the rock dust produced by the grinding action of the ice, in the water.

Boulder Clay

The amount of material transported by continental ice-sheets is enormous and this is deposited where the ice melts to form *boulder clay* or till, consisting of boulders, pebbles and even fossils, in a matrix of clay. Examination of the *erratics* found in the boulder clay, that is, rocks foreign to the area to which they have been transported, gives evidence of the direction of ice movement. For example, in certain exposures of boulder clay near Ipswich the upper part of the section is white, the lower part a drab grey. More careful examination shows that the upper bed is full of fragments of chalk and that this rests with a clean-cut junction on till composed mainly of dark clay. If erratics are collected from the two beds and compared, it is found that there are considerable differences. Those from the upper bed are mainly rock types found in Lincolnshire and northern Norfolk and therefore the ice which transported them must have come from a north-north-westerly direction. But the erratics of the lower bed can be matched by the rocks outcropping around Cambridge to the west-north-west of Ipswich. A change in the direction of ice movement has therefore been proved by the study of the erratic content of these two boulder clays. The direction of ice movement can also be proved if *glaciated pavements* can be found. These are surfaces of rock, hard enough to be smoothed and polished by the ice and showing striations caused by the harder rocks dragged across them by the ice. The direction of movement can often be determined by rubbing the finger tips lightly over the surface, which will feel rougher against the direction of flow. The striations are often crudely nail-shaped, tapering away from a distinct depression. The 'head' of the nail is upstream and marks the place where the erratic was pressed into the pavement, only to be ground away as it was carried along.

Boulder clay is usually deposited as a more or less level sheet, filling in and hiding any irregularities in the underlying surface.

But in areas where the ice was thin near its margin the boulder clay occurs only in the valleys and the country rock is exposed on the hills.

Boulder clay country is not always flat and monotonous. The aptly named 'basket of eggs' topography is produced by large numbers of low hills with smooth sides and rounded ends. The longer axes of these mounds or *drumlins* are all roughly parallel to one another and to the direction of ice flow, whilst the blunter or stoss ends point upstream. Some drumlins are composed entirely of boulder clay, others have a core of solid rock with the glacial drift wrapping round it. They are formed by ice which was very heavily charged with debris. Any outcrop of solid rock would form an obstruction round which debris would pile up, to be smoothed by the flow of the ice past it. Patches of drift which the ice was unable to move any further would similarly serve as the core for a drumlin. Excellent examples of drumlins are to be seen in the Vale of Eden to the east of the Lake District and in northern Ireland to the south of Lough Neagh.

Where the ice flowed round larger obstructions '*crag and tail*' may be produced with the stoss end forming the crag and a long tail of drift stretching to the leeward. The steep face of Castle Rock, Edinburgh, is a superb example of this with the 'Royal Mile' sloping down to Holyrood Palace built upon the tail.

Boulder clay areas are sometimes diversified by low ridges traceable perhaps for many miles. Sections show that they are built up of sand and gravel, which must have been deposited by flowing water for the pebbles are well rounded, whilst the sands are often strongly current-bedded. Such ridges or *eskers* must have been formed by subglacial streams. Some eskers are *beaded*, widening suddenly and then continuing at uniform width for a considerable distance, before widening again. The 'beads' must represent places where the ice front was stationary for a period so that a small delta was built out.

These subglacial streams are often under a considerable hydrostatic pressure which is suddenly reduced when the water issues from the ice front. The carrying power of the stream is therefore suddenly decreased and an irregularly shaped mound or *kame*, of well sorted and rounded material, is built up, more or less parallel to the ice front. The surface of kames is often dimpled by depressions or *kettle holes*, marking the site of masses of ice covered by the sand and gravel. When the ice melted, the surface of the kame would cave in. Kettle holes are not restricted to kames, but are also to be

seen in areas of 'hummocky drift', which do not show the regularity of true drumlin topography.

The vast quantities of melt water issuing from an ice front lay down deposits, either in the form of terraces or as more steeply sloping deltas and outwash fans. Such deposits are called *fluvio-glacial* for the unsorted, striated and often angular material carried by the ice has been, to some degree, sorted and rounded by running water. With increasing distance from the ice front, the features characteristic of material transported by ice gradually disappear and fluvio-glacial deposits grade into true fluviatile sands and gravels.

Boulder clay is usually either unstratified with the erratics scattered haphazardly through it or it may show a crude stratification with the erratics tending to be concentrated along certain layers. Such material must have been formed by the melting of an ice-sheet which was either stagnant or able to move freely, though perhaps extremely slowly. But in some areas boulder clay is seen to be both stratified and strongly flexured. The cliffs to the west of Cromer in Norfok provide most spectacular sections of '*Contorted Drift*' with folds, overfolds and thrusts of every kind and size in the sands and clays between great erratic blocks of chalk, often hundreds of yards in length. These cliffs give a most vivid picture of an ice-sheet driving against an obstruction, which was overridden, but in so doing the lower levels of the ice were subjected to such intense pressure that they were folded and contorted, whilst blocks of the ice were driven forwards along inclined thrust planes.

The Retreat of an Ice-Sheet

As an ice-sheet melts back or retreats towards the mountains it deposits its load either as sheets of boulder clay or as hummocky drift, with drumlins and eskers of rarer occurrence. The retreat is usually interrupted by halts, when the ice front remains stationary for a period long enough for the formation of a *terminal moraine*. A good example is the low sand and gravel ridge stretching across the Vale of York; a ridge which provides an easy east to west route across the heavy boulder clay country to the north and south and so the city of York grew up at the river crossing through the ridge.

The drainage system that develops on the surface of the boulder clay may be markedly different from that in existence before the advance of the ice. The direction of the rivers will be determined by irregularities in the surface of the drift. If only the valleys have been filled, then the postglacial drainage will follow, in general, the preglacial lines, though patches of drift, particularly stiff and

difficult to remove, may obstruct the rivers and cause *diversion of drainage.* An example of this on a small scale is shown on Fig. VI, 2. But if the drift completely covers the preglacial topography, then the new drainage may be entirely unrelated to that of preglacial times. Borings for water or other purposes may pass through an unexpectedly great thickness of drift if they happen to be on or near the line of a preglacial channel (Fig. VI, 2).

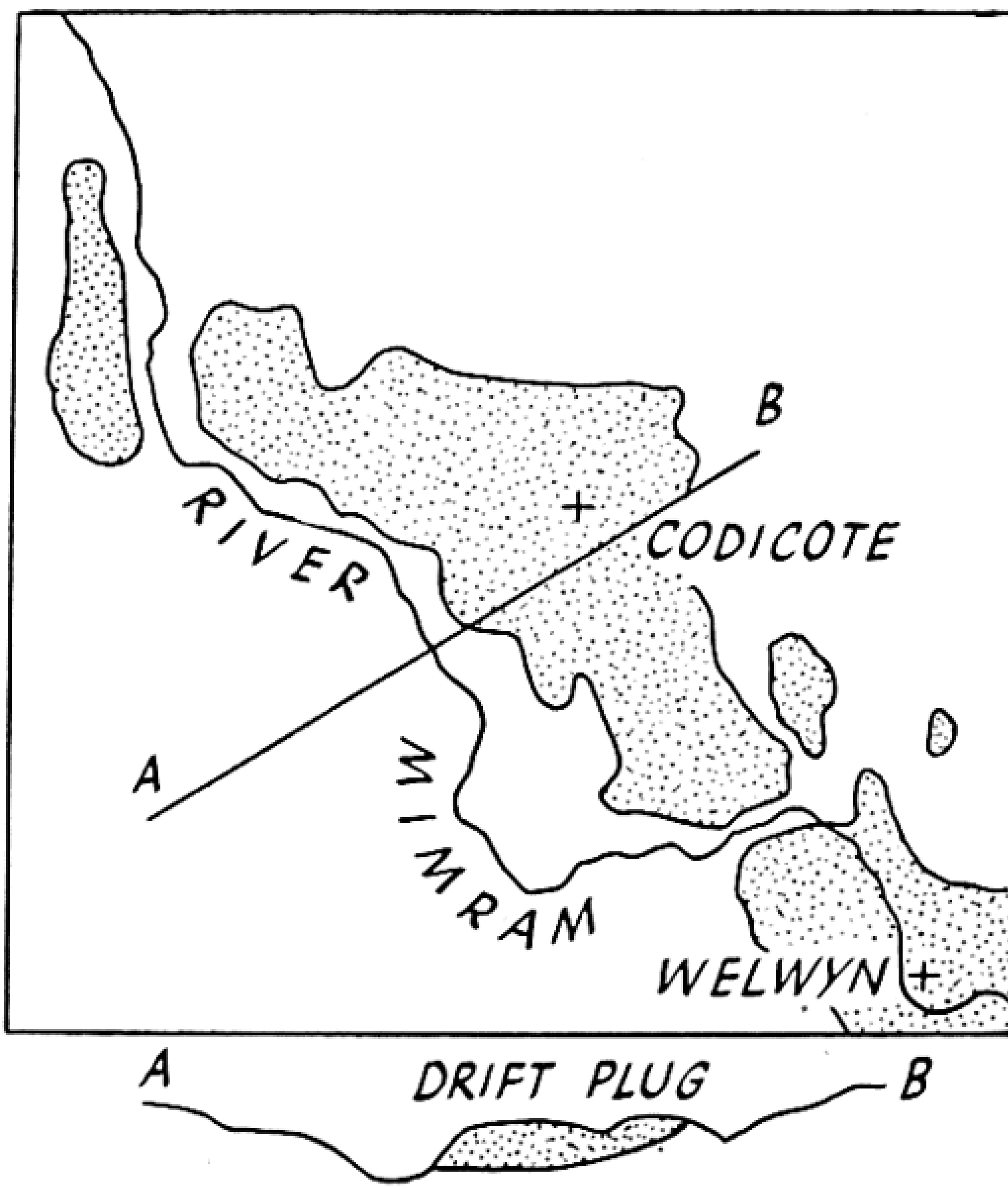


Fig. VI, 2.—Diversion of the River Mimram at Codicote in Hertfordshire by a Plug of Glacial Drift (after Wooldridge)

Greater modifications of drainage will occur if *glacial lakes* have been formed by melt waters held up between high ground and the ice front. The rising water may eventually escape by cutting an *overflow channel* through a col or gap in the high ground. The rush of the water will quickly rip out a steep-sided flat-floored valley even through very hard rocks. The glacial lake may be completely drained by this overflow channel or it may have merely discharged into a neighbouring valley and there a new lake will form at a lower level, only to escape in its turn by the cutting of another overflow channel.

Overflow channels can therefore take several forms. They may be notches cut through spurs and be now dry and completely

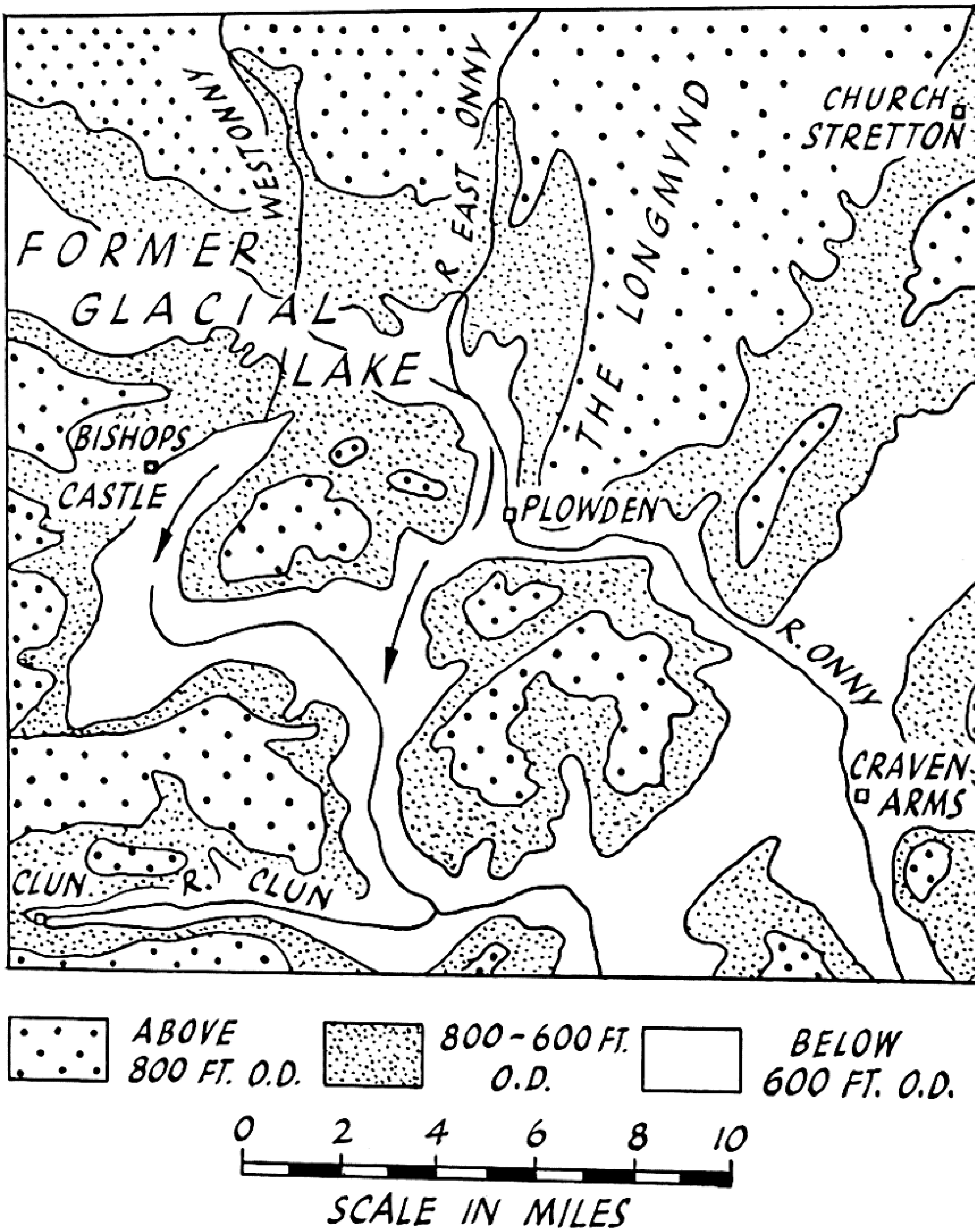


Fig. VI, 3.—GLACIAL DIVERSION OF THE RIVER ONNY IN SHROPSHIRE (AFTER DWERRYHOUSE AND MILLER)

The West and East Onny Rivers formerly joined the River Clun as indicated by the arrows. Spill waters from a glacial lake cut an overflow channel near Plowden and the combined Onny River now flows through this gorge to ioin the River Teme near Ludlow.

unrelated to the present drainage or they may be at a lower level and occupied by rivers, whose course cuts across the direction of the preglacial drainage as shown by the wind gaps left by the diverted streams (Fig. VI, 3). Overflow channels are usually the best evidence for the former existence of glacial lakes, for these were usually not in existence long enough to deposit much material. Occasionally, however, varve clays (p. 183) can be found on the floor of the suggested lake basin, or more rarely still, traces of beaches may be seen on the surrounding hills.

The largest case of glacial diversion in the British Isles is that of the River Severn which in preglacial times joined the River Dee to flow into the Irish Sea. During the retreat of the ice a large lake, 'Glacial Lake Lapworth', was ponded up against the high ground between the Wrekin and the Longmynd. An overflow channel at Ironbridge was opened across this high ground and now the Severn flows through the Ironbridge Gorge to join the Avon on its way to the Bristol Channel. Numerous other examples of overflow channels have been described from most of the hilly areas of the British Isles.

As the ice-sheets retreated back into the mountains, they finally split up into a number of valley glaciers and when these, in their turn, melted the topography of the mountains had been greatly altered. A valley eroded by stream action is typically *V-shaped* in form with the spurs interlocking and preventing one from seeing far along the valley floor. Tributary streams are normally graded to the main valley, whose floor is part of a smooth curve, though locally waterfalls and rapids may occur. But glaciation changes all this, for the ice widens the main valley, by blunting the ends of the spurs, into a *U-shaped* cross section. The depth to which ice can erode is determined by the volume and load of a glacier and not, as in the case of stream erosion, by a base-level. Glaciated valleys are therefore often *over-deepened* as compared with their tributary valleys, which are left 'hanging' with their streams cascading down the nearly vertical walls of the main valley. The profile of the valley is also changed from a graded curve to an alternation of basins, formed where scouring by the ice has been particularly vigorous, separated by rock steps. A chain of lakes often occurs in such a glaciated valley, the lakes being sometimes held up by a rock barrier at the top of a step, while others are dammed by the moraine deposited during a brief halt of the retreating ice. Other moraines form heaps of drift extending across the valley, a further contrast to an unglaciated valley, in which the river deposits are

parallel to the valley floor. The rocks outcropping on the floor and sides of the valley have been smoothed and polished by the passage of the ice to form *roches moutonnées*, with their stoss ends rounded whilst the plucking of blocks has made their lee ends steep and irregular in shape, a marked contrast with 'crag and tail'.

The ridges between the glaciated valleys will have been sharpened by the frost wedge into arêtes, and the valleys will end in great armchair-shaped hollows, with vertical sides and a flattish floor, often occupied by a lake.

Such *corries*, cwms or cirques are perhaps the most characteristic land form of mountain areas that have been glaciated. They have developed from slight depressions in which patches of snow were able to lodge. These depressions were enlarged by *nivation*, the thawing of some of the snow and then the freezing at night of the melt water which had penetrated into the cracks of the rocks. As the wedged-off fragments were carried away by slipping of the snow and by melt water, the depression gradually became larger and its sides steeper. More and more snow could accumulate in it, until the lowest levels were compacted into ice and a glacier developed. The growth of the corrie could now proceed more rapidly, for the formation of a deep terminal crevasse or *bergschrund*, separating the névé from the rock wall, enabled the freeze-thaw process to be effective over a greater surface, whilst below this plucking action was at work. The walls of the growing corrie steadily bit deeper into the mountains until finally neighbouring corries were separated by pyramidal peaks or *horns*. The Matterhorn in the Swiss Alps, with its 5000-feet precipices separated by narrow ridges, is the type example, whilst Mt. Everest shows the same features on an even grander scale. Such horn peaks can only develop after a very long period of corrie recession.

The effect of glaciation is therefore to modify profoundly the preglacial landscape. Corrie formation and the frost wedge erode the mountains to produce a much more rugged topography, deeply trenched by valleys worn and widened by the glaciers. The products of the erosion were carried by the glaciers to the lowlands, and there deposited to obliterate partly or completely the previous land surface. In the British Isles, as in other parts of the World, the finest mountain scenery is to be found in those regions which have been recently glaciated, whilst as we have seen the drainage plan and many other features of much of lowland Britain have been profoundly modified by the ice.

So far we have treated the last glacial period as if it was a simple case of ice-sheets developing and then melting. But the story is much more complex than this. As will be shown later (p. 278) there have been great fluctuations of climate during the last million years, with a number of glacial periods separated by interglacial periods, when the climate was perhaps even warmer than it is now. But the land forms that we can study are mainly those produced during the last advance and retreat of the ice, for each successive ice-sheet must have stripped off and incorporated in its own debris the unconsolidated material laid down during earlier glaciations, whilst erosion, including fluviatile erosion during the interglacial episodes, was steadily biting deeper and deeper into the mountains and destroying the land forms produced at an earlier date. The last retreat of the ice was, geologically speaking, so recent that the land forms produced, whether by erosion or by deposition, are beautfully fresh and have not been appreciably blurred by post-glacial weathering.

Periglacial Conditions

It has been increasingly recognized in the last few years that the effects of glaciation are not restricted to the areas actually covered by ice. Climatic conditions are very severe for a considerable distance from the ice edge. Spitzbergen, Alaska, northern Siberia and Canada are today within the *permafrost* belt, where the ground is permanently frozen to depths of hundreds of feet. But during the summer after the melting of the snow cover, the upper few feet of the ground thaws. The melt water cannot drain downwards through the still frozen zone beneath so the ground surface becomes a morass. Mixtures of liquid, semi-frozen mud and stones begin to flow down every slope, even the most gentle, and there is a mass movement of material towards the valleys.

The cliff behind Black Rock, Brighton (Fig. VI, 4), shows a section in a mass of blocks and pebbles of chalk set in a mixture of sand and chalk pellets, banked up against a partially buried cliff cut in undisturbed Chalk. The stratification planes of this 'coombe rock' dip gently away from the old cliff face. Chalk is very soft and soon disintegrates when it is transported by water, but if it is frozen then it is much more resistant. The coombe rock must therefore have been formed by a semi-frozen mixture of chalk and sand, sludging over and partially burying the old cliff line. Similar evidence of *solifluxion*, as this process is called, can be found in many other places. The deposits are sometimes strongly contorted, showing

that the moving mass must have been very viscous. The pebbles often have their longer axis vertical in marked contrast to water-laid deposits in which the pebbles lie horizontally, but pebbles sinking into thawing mud would tend to turn so that they were vertical.

Whilst solifluxion deposits are badly sorted and in this respect resemble boulder clay, they do not contain erratics but are composed of material of local origin. The name 'coombe rock' has long been applied to the chalk-rich debris of downland areas, but it is only a

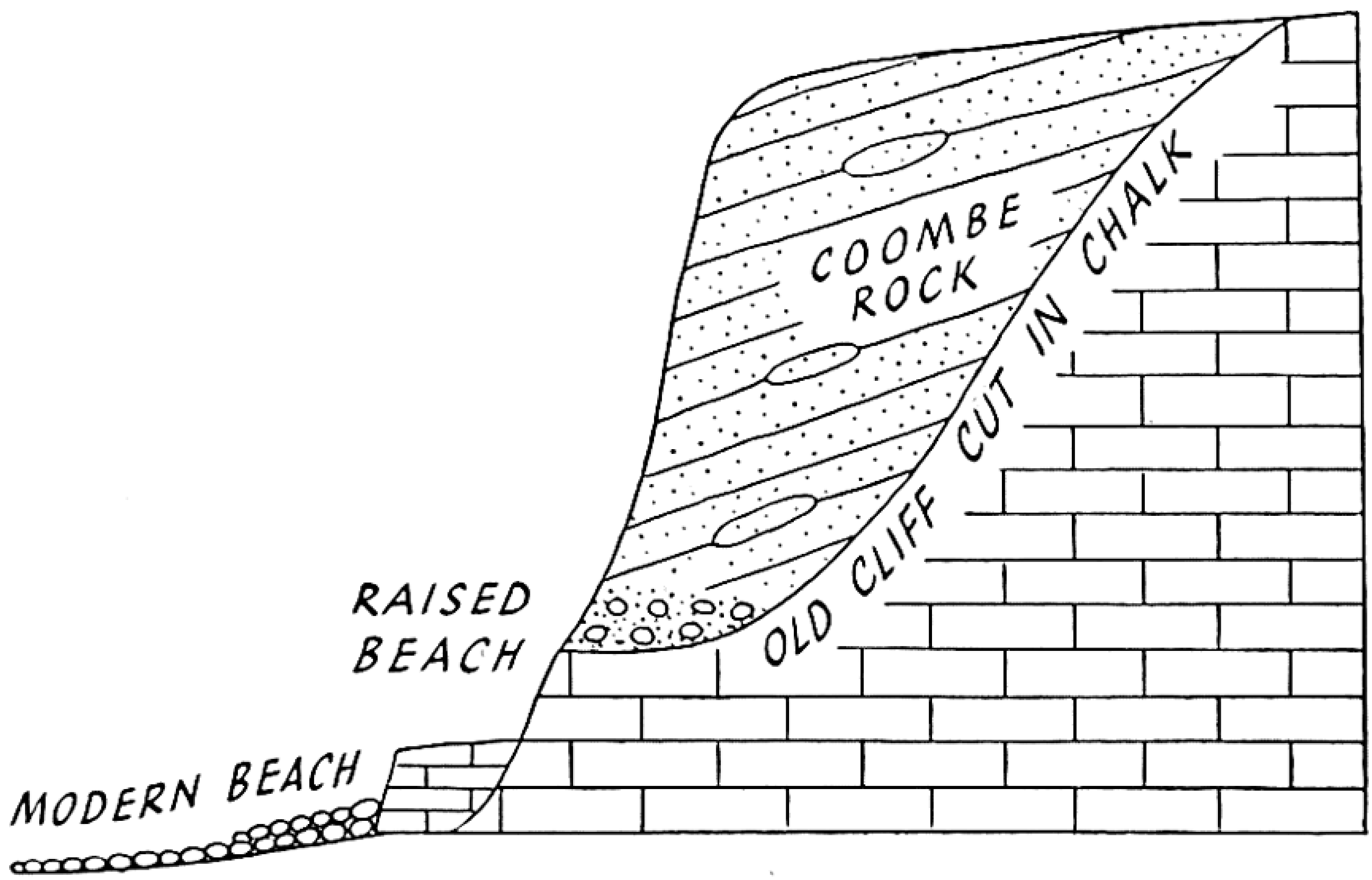


Fig. VI, 4.—Section at Black Rock, Brighton (after Osborne White)

local variant of *head*, the term given to all solifluxion deposits whatever their composition.

The section at Black Rock has been instanced, for it is well south of the maximum extent of the ice-sheets, which did not pass beyond a line joining the estuaries of the Thames and the Severn. Spreads of head are extensively developed throughout southern England. They must have been formed when southern England was in the zone of permafrost. We have already seen (p. 65) that a considerable part of the cutting of the dry valleys of the Downs must have taken place during the same period, whilst many of the coombes cut into the scarp faces of the Downs have a corrie-like shape and were formed, in part at least, by nivation. Further north,

head is often found resting on boulder clay, showing that the periglacial zone must have extended northwards as the ice-sheets waned.

But periglacial conditions have also produced mass movements of rocks on a much bigger scale. In many areas of gently dipping strata, such as the Northampton Ironstone Field and the Weald, dips in unexpected directions can be observed on the sides of valleys. Beds, which lie as a uniformly inclined sheet on the ridges, steepen as they are followed towards the valleys and the direction of dip may also change and slope valleywards, whilst in the floor of the valleys sharp anticlines may be found. Borings have shown that the rocks at greater depth are unaffected by these *superficial structures*

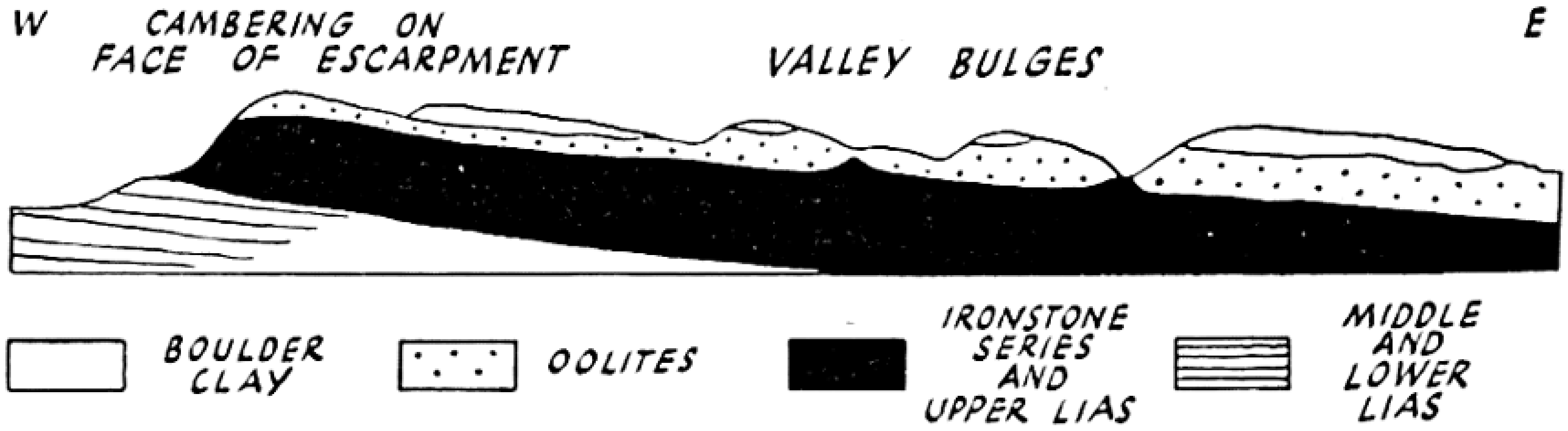


Fig. VI, 5.—Section (after H.M. Geological Survey) Showing Superficial Structures in the Northampton Ironstone Field

which die out downwards. Moreover, both the *camber* sheets, dipping valleywards, and the *valley bulges* (Fig. VI, 5) are clearly related to the present topography, the axes of the valley bulges changing their direction as a valley swings.

Such structures, together with *landslipping* of the rotational type with inward dipping beds along the base of escarpments, are developed when a thick massive competent bed overlies softer and plastic incompetent strata. The competent rocks must have moved valleywards on the surface of the incompetent beds, which if squeezed sufficiently give rise to valley bulges. Much of this movement must have occurred during periglacial conditions, when 'freeze-thaw' penetrated downwards to a considerable depth and so weakened the stability of the rocks as to cause movement either in the form of cambering or landslipping.

CHAPTER VII

Action of the Sea

THE effects of *marine erosion* are only too apparent on many parts of our coasts. Around Cromer and Lowestoft in East Anglia, roads and houses are disappearing into the sea as the cliffs advance inland at a rate averaging more than 1 foot per year, whilst spectacular and disastrous changes may result from a single great storm.

Winds cause the water particles of the ocean surface to move in circular orbits. Waves are produced, for at any one instant of time some particles are at the bottom of their orbit, others are moving upwards, some are at the crest and others are moving downwards. All particles along a line are in the same relative position in their orbits, so wave crests separated by troughs (where the particles are all at the bottom of their orbits) are produced. The succession of waves and troughs will move in the direction of and at a speed proportional to the strength of the wind.

With increasing depth of water, the size of the orbits decreases until at a depth equal to the wave length (distance from one crest to the next) the movement is so small that the water is virtually at rest. This depth may be as great as 600 feet in the case of the storm waves of the open sea. Once waves have been generated as *forced waves* by storms, they may travel for thousands of miles across the oceans as *free waves* or *ground swell* until they break on a coast.

As waves approach a coast, the water usually shallows and the depth may become less than the wave length. Frictional retardation will then change the orbits gradually from circles to ellipses. The wave front will become steeper and steeper and finally the wave breaks. The mass of broken water rushes for some distance up the shore and then sweeps back down the slope as the backwash. The

pebbles on a beach on which a strong sea is breaking are constantly in movement, being carried forwards by the waves and then swept backwards.

The erosive force of the waves lies not so much in the actual blow of the breaking water, strong though this may be, as in the pebbles and boulders which are picked up, hurled forwards against the cliff and then washed backwards to be used over and over again and at the same time ground smaller. Any air in the fissures of well-jointed rocks is suddenly compressed by the mass of water trying to enter the fissures. This hydraulic action means that the disruptive effect of the blow of the wave is not restricted to the actual face of the cliff, but is felt for some distance behind it. *Blowholes* spouting spray during heavy seas may be developed well behind the cliff edge and also may occur on the cliff face. At Boscastle in Cornwall such a blowhole can be seen throwing out at the right state of the tide a plume of spray as the trough of each wave passes, owing to the expansion of the air which has been compressed as the preceding wave crest surged past.

Wave action is extremely efficient in etching out any differences in the hardness of the strata forming the coast. Bays are worn out along the outcrops of the softer beds, whilst the cliffs produced by the more resistant beds are rarely perfectly straight but show small indentations along the line of major joints, fault planes and other lines of weakness. The coast is always strongly indented where it is at right angles to the strike of the beds, for the sea has then the maximum opportunity to attack a considerable variety of rocks in a relatively short distance.

The term *Atlantic coast*, which is sometimes applied to this type of coast, is not a particularly happy one, for whilst the coasts of the Atlantic often do cut across the strike of the beds, this is not always the case and the coasts of other oceans frequently show this relation. If the strike of the strata is parallel to the coast, then the so-called *Pacific Coast* is produced. Such coasts are usually much straighter, for the sea is attacking more uniform material, but if the waves are able to breach the cliff line produced by a resistant stratum, they will rapidly erode any softer rocks behind and will produce bays, whose maximum width is along the strike of the softer beds, whilst to seaward a line of islands and rocks marks the position of the old cliff line.

On Fig. VII, 1, is shown part of the coast of Dorset. A typical Atlantic type coast is developed around Swanage, a Pacific type to the west of St. Alban's Head with Worbarrow Bay, Mupe Bay and

Lulworth Cove eroded along the strike of the soft Wealden Beds and the Man-o'-War and other rocks marking the line of the Portland Limestones where they have been breached.

Cliffs are being constantly attacked, not only by the waves, but also by the agents of subaerial erosion and therefore the profile of cliffs is determined by the rate at which the two agencies act. If one walks along the beaches on either side of Cromer on a day of heavy rain, perhaps with the wind offshore and sea comparatively calm, the cliffs of soft sand and clay can be both seen and heard to be steadily wasting away owing to the slipping of waterlogged patches aided by the loosening effect of the sand dashed against the cliffs by

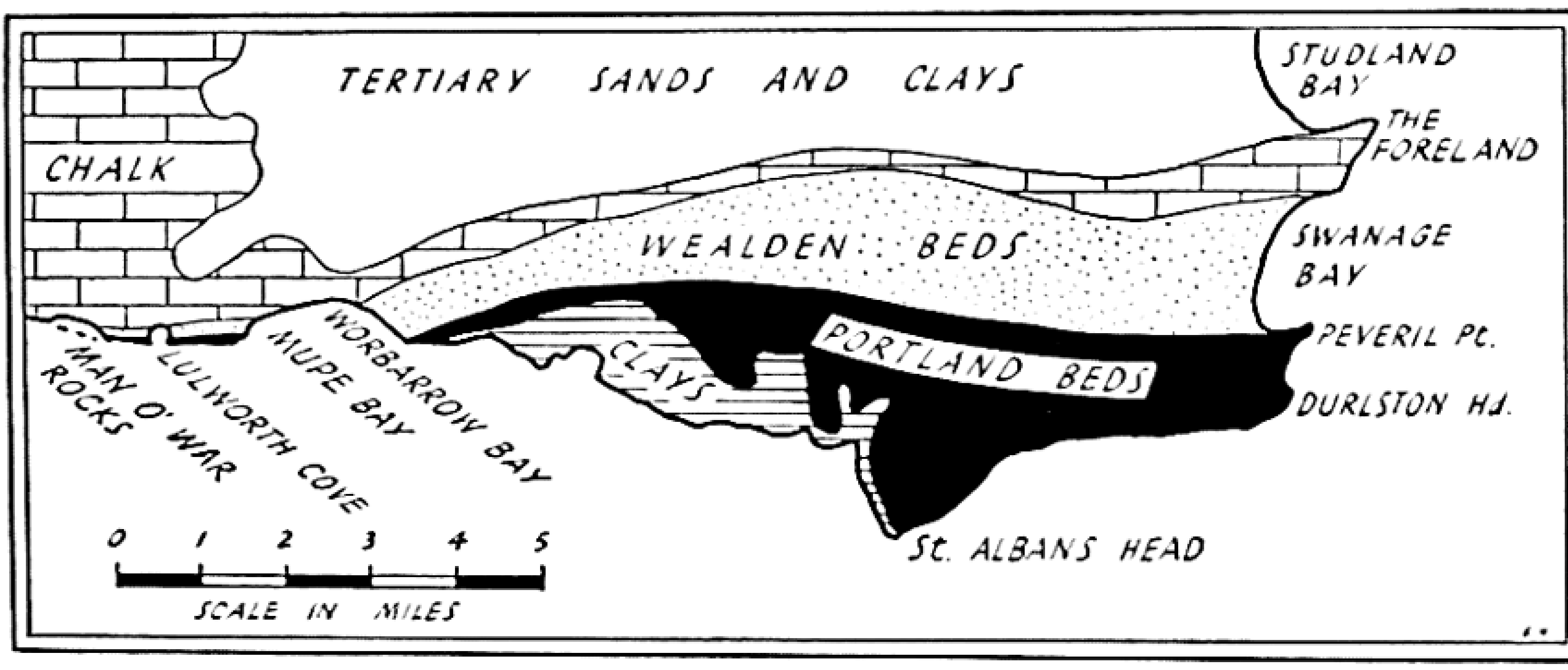


Fig. VII, 1.—Differential Marine Erosion on the Coast of Dorset
The Chalk and Portland Beds are resistant, the other beds are much softer. Note the 'Atlantic' type of coast to the north of Durlston Head and the 'Pacific' type around Lulworth Cove.

the eddies. But the slipped material is not allowed to stay for long at the angle of rest, for it will be attacked and removed by the next high sea and therefore a fairly steep cliff line is maintained.

Really steep cliffs will only be produced when the rate of wave attack undercutting their base is more rapid than the rate at which the upper part of the cliffs is worn back by subaerial erosion. Vertical cliffs are normally only developed in resistant rocks lying horizontally. If the beds dip landwards, the cliffs will have a stepped profile being made up of a succession of dip and scarp faces, whilst a seaward dip will facilitate the fall of blocks undercut by the waves and an overhanging profile will result (Fig. VII, 2).

Wave action is concentrated in a narrow belt at the foot of the cliffs, so that in hard rocks a distinct *wave-cut notch* will be produced at about high water mark. As the cliff retreats inland a *wave-cut*

platform of bare rock, usually exposed at low tide, is formed. The surface of the platform is rarely completely level, for it is seamed by gullies eroded along joints and above it may rise stacks corresponding

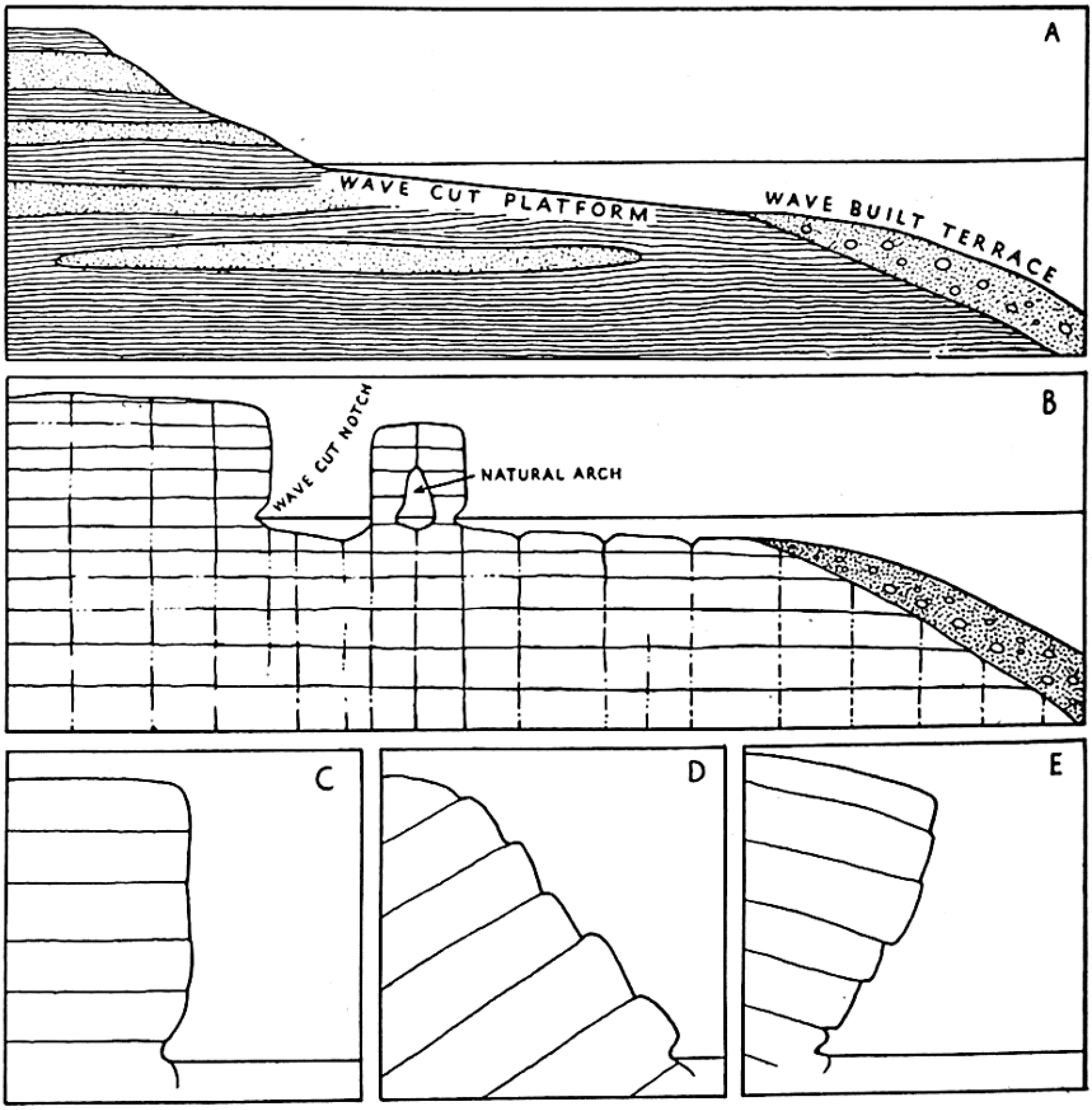


Fig. VII, 2.—The Effect of Structure on the Profile of Cliffs

A. Sloping cliffs cut in soft rocks.
B. Steep cliffs cut in well-jointed hard rocks. Erosion along joints has grooved the wave-cut platform and controlled the shape of the stack with a natural arch etched out along a 'master' joint.
C. Vertical cliffs cut in horizontal strata.
D. Stepped cliffs cut in strata dipping landwards.
E. Overhanging cliffs cut in strata dipping seawards.

Note the wave-cut notches at the foot of cliffs in hard rocks.

to the outliers left behind by a receding escarpment. The material from the cliffs, when it is small enough, is dragged backwards by the undertow across the wave-cut platform to form in deeper water the *wave-built terrace* (Fig. VII, 2).

Marine Deposition

The effects of wave attack are therefore not solely erosional. *Storm beaches* are built up at the foot of cliffs. The majority of the pebbles are extremely well rounded and are pitted by small chatter marks due to the battering against each other which they have sustained. The pebbles are usually very well-graded (all about the same size) for they have been thrown forward by the biggest waves and are too big to be dragged seawards by the backwash, which has removed all material below a certain size.

When the wave fronts strike a coast obliquely, material is carried forwards by the waves, but is swept down the steepest slope, usually at right angles to the beach, by the backwash. Pebbles and sand are therefore moved in a zig-zag manner along the coast by the process of *Long Shore Drift*. But if the carrying power of the waves decreases, then the transported material will be deposited. *Spits* are built out on the sheltered sides of headlands or in the sheltered water behind an island which thus becomes tied to the land. Deposition often takes place rapidly enough to divert the mouth of a river, which is forced to flow parallel to the growing spit until it can maintain an open channel to the sea. The direction of long shore drift is determined by the direction of *fetch*, that is, the maximum open water path over which waves can travel to reach the particular piece of coast. The direction of fetch is not necessarily the same as the direction of the prevalent (most frequent) winds, for waves following a fairly short path will not have the same transporting power as waves rolling in, but less frequently, from a greater distance.

Along the coasts of the English Channel the direction of fetch and of the prevalent winds are the same, both from the south-west. Spits and beaches extend eastwards and the mouths of many rivers, as for example the Arun and the Adur (*see* Fig. V, 5), are diverted eastwards. The growth of spits and the movement of beach material is to the south along our North Sea coasts, for the maximum fetch and the severest gales, though not always the prevalent winds, are from the north-east.

Provided that there is a plentiful supply of material, spits can grow at a surprising rate. Orford Ness in Suffolk is an excellent example, for historical evidence enables us to fix the position of the end of this spit at several dates. In 1165 Orford Ness Castle was built on the shores of a small harbour at the mouth of the River Alde sheltered slightly by a spit, which had already deflected the mouth of the Alde southwards for five miles from Aldeburgh. By 1600 the spit had grown southwards for a further three miles and the

prosperity of the harbour had declined long before this. Since 1600 the spit has added another mile and a half to its length, so that in all the Alde has been diverted nearly 10 miles to the south, four and a half miles of this having taken place in less than 800 years.

The growth of spits proceeds intermittently rather than steadily, periods or rapid growth being followed by a pause or even by erosion. Low ridges of shingle or fulls, often at an angle to the length of a spit, mark places where the end of the spit has remained stationary for a considerable time. Many spits, as for example Scolt Head Island and Blakeney Point on the Norfolk coast, are extremely complex in plan with ridges of sand and shingle, marking the former ends of the spit, and projecting into the partly silted-up lagoons which have developed on the landward side of the spit (Fig. VII, 3). Even larger examples of the deposition of shingle with the formation behind them of large, partially or completely infilled lagoons, are the forelands like Dungeness or shingle banks like Chesil Beach (Fig. VII, 3).

Therefore whilst parts of our coasts are receding before the attack of the waves, in other areas the land is gaining on the sea and it is estimated that on balance there is probably, at present, no great change in the surface area of the British Isles. But the areas of *accretion* (land gained from the sea) are all very low-lying and usually have to be protected by man-made defences. As was shown so disastrously in February 1953 a single storm, aided by an exceptionally high tide due to an unusual combination of circumstances, may break through these barriers and submerge great areas. Coasts of accretion are therefore liable to rapid and considerable changes under natural conditions and can only be stabilized by man's activities.

Coastal Protection

Coastal defences are both extremely expensive and laborious to construct for they have to be very strong to resist the battering of storm waves and must be carried down to a considerable depth because of the undercutting and scouring action of the sea. Every year there are reports of heavy gales damaging and weakening the defences somewhere along the coast.

The first principle of coast protection is to retain any shingle that is accumulating, for this takes the first blow of the waves and indeed a wide and high shingle beach may well be sufficient defence. But beach material is always liable to be moved along a coast by long shore drift. *Groynes* built out at right angles to the coast will trap and retain the shingle and sand, provided that they are closely

enough spaced to prevent erosion from taking place on their lee side. But the building of groynes and breakwaters in one place may mean increased erosion further down the coast. The construction of break-

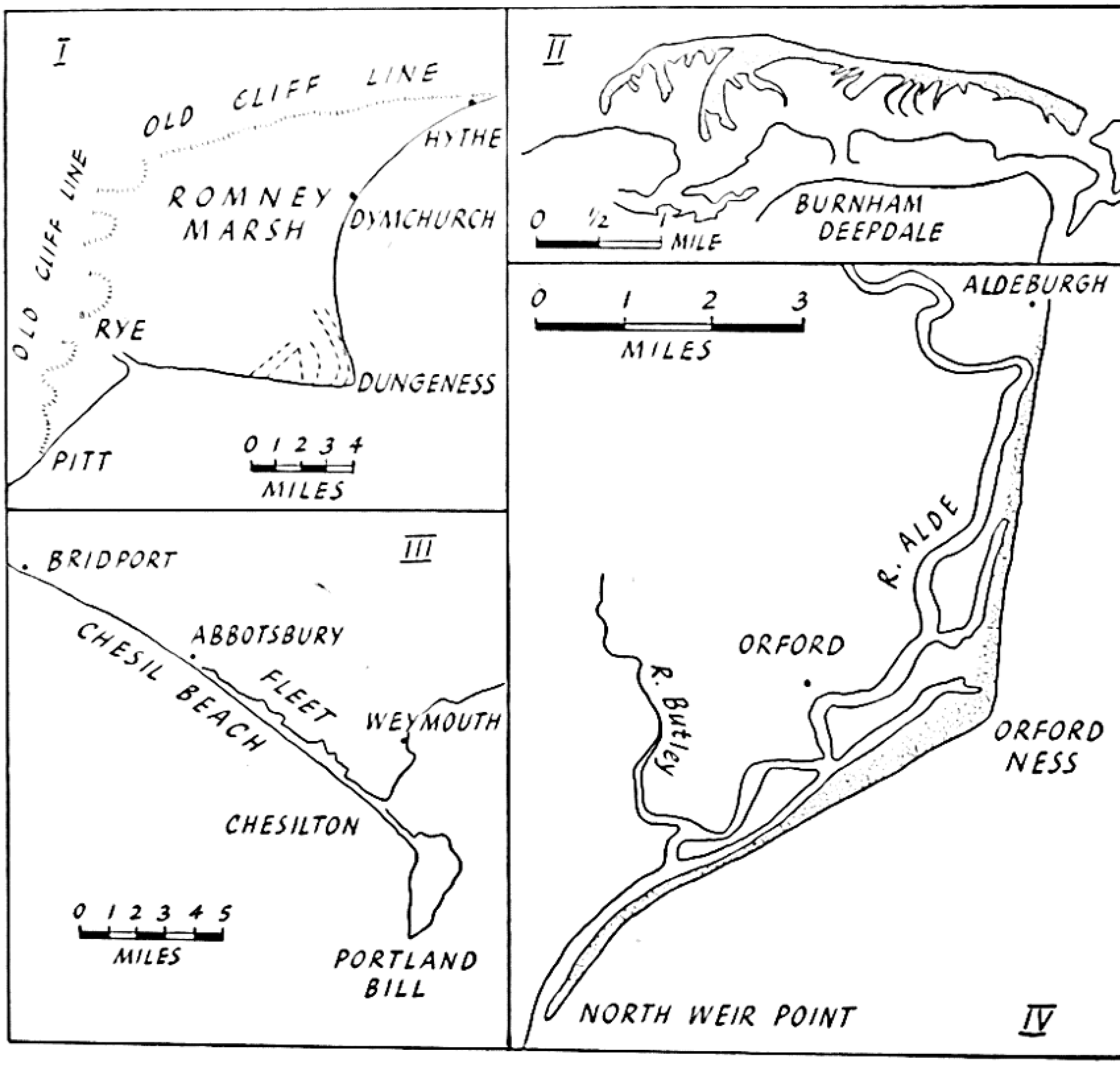


Fig. VII, 3.—EXAMPLES OF MARINE DEPOSITION

I. The cuspate foreland of Dungeness (after Lewis). The broken lines mark 'fulls', which are being eroded to the west of Dungeness.
II. Scolt Head Island in Norfolk (after Steers); a compound recurved spit.
III. Chesil Beach, Dorset, extending from Bridport to Chesilton, with the lagoon of the Fleet behind it for part of its length.
IV. The southward deflection of the mouth of the River Alde by Orford Ness, Suffolk.

waters at the entrance to Lowestoft Harbour has been followed by extremely rapid recession of the coast (520 feet between 1905 and 1947) at Pakefield a few miles to the south, for the shingle moving down the coast from the north was trapped and the soft cliffs further south were left unprotected.

Coastal works should therefore not be planned on too parochial a basis. If possible they should be continued until they can be firmly tied to a more resistant part of the coast as otherwise the sea may be able to work in behind them, and also the possibility that protection at one point may cause erosion elsewhere should be firmly borne in mind. Only in areas of excessive accumulation should the removal of beach material be permitted, otherwise after a period of years this may lead to erosion and costly protective works.

Breakwaters not only provide shelter from storms but also help to keep open the mouths of harbours which would otherwise be obstructed by long shore drift. An excellent case is provided by Liverpool, where the construction of a double line of massive walls built of limestone extending for twelve miles into Liverpool Bay has been nearly completed. The object is to prevent the deep water channel into the Mersey from being silted up by the material brought by the tides and long shore drift. Canalization of the river waters will concentrate their scour between these retaining walls and, it is hoped, keep the channel clear with a minimum of dredging.

Change of Sea-Level

No mention has been made so far of change of sea-level, but in some areas there is clear evidence that this has occurred during historic times, whilst the evidence from the recent geological past is much more widespread. On the shores of the Bay of Naples stands the ruined Temple of Serapis built by the water's edge about 105 B.C. At the close of the 15th century the Temple was submerged to a depth of 23 feet, the maximum height of the borings of marine shellfish into the pillars. But in 1538, after an eruption of the nearby volcano of Vesuvius, the Temple was uplifted well above sea-level. Since then slight subsidence has occurred and today the sea just floods on to the floor of the Temple.

It is usually very difficult to be sure whether a change of sea-level is due to vertical movement of the land only or of the sea only or of a combined movement involving both the land and the sea. It is therefore preferable to speak of a *positive movement* rather than of a rise and of a *negative movement* rather than of a fall in sea-level, for the sense of the movement relative to present sea-level is stated without any assumption as to the nature of the movement.

The west coast of Scotland is fringed more or less continuously by a magnificent series of *Raised Beaches*, consisting of level terraces in places covered with typical beach shingle and backed by an uplifted cliff line often with caves cut into it and with stacks in front, exactly

similar to the features of the existing beach below. The lowest beach at about 25 feet above present sea-level is sharp and clear, but the higher beaches at about 50 and 100 feet above present sea-level must be older, for they are not so perfect and are often slurred over by downwash.

Along the coasts of southern England, raised beaches are to be seen at only a few places, including Black Rock, Brighton (Fig. VI, 4), where the head rests on a foot or so of typical beach shingle from which can be collected the shells of cockles, mussels, etc. The beach rests on a platform cut at about 25 feet above sea-level in the Chalk. This beach and the other English raised beaches all have a covering of head and must therefore have been cut prior to the latest period of periglacial conditions, but the Scottish beaches are often cut in boulder clay, which forms the old cliff line, and therefore must be considerably later in date, which explains why they are much more continuous and less affected by erosion than the English beaches.

Negative movement of sea-level is shown by the *submerged forests* to be seen at Pitt near Hastings, in the estuary of the Dee in Cheshire and at many other places round our coasts. At extreme low tide the stumps of trees can be seen rooted in black peaty soil, in which one can sometimes find the implements dropped by Neolithic man (p. 252) a few thousand years ago, when these forests were dry land. Other evidence is given by the *Drowned Valleys*, which have been submerged, so that the sea has spread far inland. Several types can be recognized. In the heavily glaciated areas, they are of the *fjord* type with a U-shaped cross section, hanging side valleys and are sometimes shallowed near the mouth by a submerged terminal moraine. Along the 'Atlantic-type' coast of south-west Ireland, the drowned valleys are of the *ria* type, typical fluviatile valleys worn out along the strike of soft rocks. Many drowned valleys, as for example those forming the creeks of Chichester and Portsmouth Harbours (Fig. V, 5), have been silted up considerably by the rivers flowing into them. In Norman times Bosham, near Chichester, was an important port, now it can be used only by small craft at high tide. Where silting has been less rapid, as at Falmouth and Milford Haven, the drowned valleys form fine natural harbours. Fishermen often dredge up from the Dogger Bank, even from depths of nearly 200 feet, the trunks and stumps of trees like oak and birch and the bones of reindeer, mammoth, etc. Clearly the Dogger Bank must once have been dry land. Similar evidence has been found off many other coasts, additional proof of periods of very low sea-level, compared with the present, during the recent geological past.

Possible Causes of Change of Sea-Level

The volume of water in the oceans must have varied very considerably during the last million years. During glacial periods vast quantities of water were locked up in the ice-sheets, only to be returned to the oceans as the ice-sheets melted during the interglacials. It has been estimated that if all the existing glaciers and ice-sheets were to be melted suddenly this would cause a world-wide rise of sea-level of as much as 150 feet and that at their maximum extent (Fig. VI, 1) the ice-caps and glaciers contained sufficient water to have produced a fall of sea-level of more than 300 feet below the present.

Eustatic is the term applied to the change of sea-level due solely to variation in the volume of the ice-caps and not involving any vertical movement of the land. But there is clear evidence of movement of the land in many areas. In Chapter XV it is shown that the raised beaches around the Baltic are not horizontal, but are strongly warped. Scandinavia, like the other heavily glaciated areas, was considerably depressed by the weight of the ice-sheets, and since they melted has been rising owing to *isostatic adjustment. Tectonic* forces, in operation in the unstable regions of the earthquake and volcanic belts (Fig. XIV, 3), have produced considerable vertical movements of the crust during recent times. But in the stable areas, away from these regions, a sequence of raised beaches can often be followed for considerable distances at more or less constant heights above the present sea-level.

Variations of sea-level may therefore be due either to isostatic warping, or to tectonic movements or to eustatic change or to some combination of these. In certain areas there is clear evidence that one or other of the two first mentioned causes is dominant. But any mass movement of the crust must have caused a change in the total volume of the ocean basins and therefore, provided that the volume of sea water remained constant, a variation in sea-level, though perhaps of an inappreciable amount on a world-wide scale. One difficulty in considering the effects of these three possible causes is that tectonic movements are not restricted to the land areas, but also affect the sea floors and then the changes of mass produced are much more difficult to assess. Another difficulty is that we often cannot date precisely raised beaches and still less shore lines that are now submerged. If we could trace with certainty over long distances former shore lines that we knew were strictly contemporaneous, the displacement relative to present sea-level, of what was once a horizontal surface, would give us a more accurate means of assessing the

relative importance of eustatic, isostatic and tectonic movements in causing variation of sea-level.

TYPES OF COAST LINE

Coast lines can be classified genetically according to their mode of origin and the stage that they have reached in the Cycle of Marine Erosion.

Submergent Coast Lines are produced by the sea penetrating up the valleys of a land area that has been drowned by a positive movement of sea-level. The coast line will, at first, be strongly indented, wave attack will be concentrated on the headlands and during the stage of Youth the cliffing of the headlands will be proceeding rapidly. As the cliffs recede landwards, the coast will become straighter and this will be helped by the deposition of the detritus produced by the waves. Deltas will be built out by the rivers draining into the bays, bayhead beaches may be formed by the finer material carried up them by the waves and spits will develop on the sides of the headlands.

As the coast line passes towards Maturity, the retreating cliffs will have provided so much detritus that some of the spits will have spread right across the bays to form *baymouth bars*, so that the mature coast will be nearly straight consisting of stretches of cliffs separated by sand and shingle bars in front of partially or completely silted up lagoons. Both the cliffs and shingle will retreat before the waves and as the sea cuts more and more deeply into the land, the stretches of cliffed coast will increase in length. Finally when the coast line has receded past the furthest embayments produced by the original submergence, it will consist of a continuous line of cliffs with a wide wave-cut and wave-built platform at their foot. The increasing width of the belt of shallow water will steadily reduce the force of the waves and therefore during Old Age the cliff line will recede much more slowly and will be less steep owing to the greater effects of subaerial erosion.

An *Emergent Coast Line* is produced by a negative movement of sea-level enabling the waves to attack a gently sloping surface. The initial coast will be straight with an *off shore bar* thrown up by the waves cutting into the soft material of the uplifted wave-built terrace. Lagoons will form behind the bar, but they will be steadily reduced in width as the bar is pushed landwards and finally, when the coast reaches Maturity, the waves will be attacking a straight line of cliffs. The later stages will then be little different from those of a submergent coast line.

In the case of a *Faulted Coast Line* with the sea attacking the fault scarp, the initial stage will be a straight coast but one that is continuously cliffed.

Many coasts are *Compound* showing a combination of the features of both submergent and emergent coasts. This is only to be expected if we consider the very considerable amount of time needed for a coast to pass from Youth even to Maturity and the evidence given above for considerable oscillations of sea-level during the recent geological past. But the concept of a Cycle of Marine Erosion is of value for it provides a classification of coasts according to the main episodes of their history.

CHAPTER VIII

Semi-Arid and Arid Regions

IN arid and semi-arid regions, rainfall is of slight amount and very spasmodic in occurrence. Water is therefore of less importance than in humid regions as an agent of erosion and deposition, though even in deserts it cannot be completely ignored.

The rocks are broken up mainly by the physical processes of weathering and transportation is mainly due to movement under gravity or the action of the wind. The landforms produced are very different from those of regions with a greater and more regular rainfall.

SEMI-ARID REGIONS

In the semi-arid regions of the western United States block faulting has produced a number of mountain chains separated by deep basins. The products of rock weathering slide down every crack and gully along the mountain front to form *alluvial fans*, which gradually grow larger and finally join together as a continuous strip or *bajada* of rock waste. Much of the material has been transported by the infrequent but very heavy rainstorms, which sometimes rip out steep-sided channels or *wadis*. At other times the rain water pours downwards as innumerable small streams producing *sheet floods* which are capable of causing a great amount of both erosion and transportation in the short space of time between the cloud-burst and the soaking of the water into the ground. The drainage of these intermontane basins is usually completely internal, with the streams either soaking into the ground or helping to form in the centre of the basins *playa lakes*, whose size fluctuates with the rainfall. As the mountain front is worn back by erosion a gently sloping *pediment* is developed beyond the bajada. The pediment may be either cut across bare rock or may be thinly veneered with rock waste.

The Cycle of Arid Erosion

A cycle of Arid Erosion has been recognized. During the stage of Youth so much waste is carried from the uplands into the basins that the level of the latter is raised appreciably causing a reduction in the relief of the area, a marked contrast to the increase in relief during the youthful stage of the normal cycle. Basins developed by block faulting will be at different levels. At first each basin will have its own base-level, but as the basins fill up, gullies will be cut through the divides so that the higher basins will become graded to a lower level. As the uplands are worn down with the development of wide bajadas or pediments, the landscape gradually passes from Maturity into Old Age, which is reached when very little of the original mountains protrude above the sheets of rock waste or the gently sloping rock-cut platforms.

Arid Regions

In the more arid regions, such as the Sahara and Kalahari Deserts, where rain is a most unusual occurrence, the effects of the wind are much more important. The corrasion produced by the wind-driven sand grains is shown by the facetting and polishing of any pebbles lying on the surface. If the winds blow fairly consistently from one direction, these pebbles will be worn into *dreikanters* with a wide base and a triangular cross section, the ridge being parallel to the prevalent winds. Rock surfaces will be polished and may be grooved and undercut into the most fantastic shapes. The sand blast is only effective for a few feet above the surface of the ground and therefore can only fashion minor and not major topographic forms. This is because the sand grains are moved by saltation, bounding for a limited height above the surface of the desert. But within this belt any slight differences in hardness are etched out and honeycomb weathering is commonly developed. All the finer material is blown out of the desert areas, to help form the great sheets of Loess (p. 183).

Much more important are the depositional forms; *sand dunes* are built up, perhaps round some obstruction, a plant or an outcrop of rock or perhaps as the result of an eddy. Once the sand has begun to accumulate, the dune grows very rapidly as more and more sand is trapped. Dunes vary considerably in size and shape. *Barchans* are crescentic-shaped in plan with the horns pointing downwind, whilst they are assymetric in cross section with the gentler slope pointing upwind. Sand grains are rolled up this slope until they fall over the crest down the steep lee side, where material is able to accumulate in the eddy. Such dunes move steadily downwind, still retaining

their sickle shape, for they move fastest at the horns where the sand grains have the shortest distance to travel.

But in other areas, such as the Great Sand Sea lying along the Egyptian-Libyan frontier, the sand dunes are very different. They are parallel to the prevalent winds and seem to be fixed in position. Individual dunes may be many miles in length, hundreds of yards in width and a hundred feet or more in height. Their origin is as yet uncertain, but they may have rock cores which have helped to stabilize them or the winds may have fluctuated considerably and hence been unable to move in a definite direction an over abundant supply of sand.

But all deserts are not formed entirely of sand dunes, for *hamadas* or stretches of bare rock floor, grooved and scoured by the sand blast, are often of very considerable extent.

Coastal Dunes

Sand dunes are not restricted to deserts, but are also developed on those coasts, where there is a plentiful supply of beach sand carried inland by the prevalent winds. Such coastal dunes can produce very serious problems, for like barchans they are not fixed, but may overwhelm fields, woods and even villages. About ten miles to the west of Elgin on the south side of the Moray Firth are the Culbin Sands, which have moved inland since the end of the 17th century and have completely buried what was formerly a large and fertile estate. Villages are also buried beneath the coastal dunes of south-west France, the Low Countries and elsewhere. The only way to stabilize the sand is to plant it with marram grass, which will both grow on sand and also bind it into place by long roots spreading just below the surface. It is most important to keep the cover of marram unbroken, for the wind can very quickly enlarge even a rabbit hole into a 'blow out' several yards across.

CHAPTER IX

Denudation Chronology

GEOMORPHOLOGY is concerned with both the processes of land sculpture and the history of the development of the present landscape. The latter is usually very difficult to decipher, for the development of a new landscape inevitably involves the removal or burial of many of the pre-existing land forms. Raised beaches, the evidence of former periods of high sea-level, are destroyed as cliffs advance inland, river terraces may either be buried beneath the deposits of a new phase of aggradation or be removed by a river cutting vigorously into its banks. It follows that the evidence on which denudation chronology is based is often incomplete and the further back in time one attempts to trace the story the more numerous will be the gaps.

The evidence sought is of the major episodes in the evolution of the landscape. Glaciation will alter profoundly both the land forms and the denudation pattern of an area. A period of still-stand will mean the formation of extensive level areas round the coasts and in the valleys and, if base-level was stationary for a very long period, partial or complete peneplaination. The geomorphologist therefore attempts to find evidence of changes of base-level and of glaciation and to determine their relative age. He studies both the land forms and any deposits lying upon them. Usually he works from the hills down into the valleys, for fragments of the older stages will only be preserved on the high ground and the record will become more complete the nearer he approaches the present base-level.

EROSION SURFACES

If one stands on the summit of Cader Idris in Merionethshire and looks southwards towards central Wales the view is in one sense

rather disappointing, for with few exceptions the mountains all rise to the same height. This *accordance of summit levels* cannot be just chance, for the mountains have been carved out of a variety of rocks of differing hardness, whilst the geological structure of the area is complicated. One would expect that the outcrops of the more resistant rocks would produce higher summits than those formed by softer beds. But this is not the case. All the mountain tops have been planed off at about the same level and this can only have been the result of a period of peneplaination—so long ago that this 'summit plain' has since been uplifted to about 2000 feet above sea-level and has been so deeply dissected that in some areas the hills have been worn below this level and all traces of it have been destroyed.

In parts of south-eastern England summit plains are much more extensive. The Chalk downland between the Kentish or Great Stour and the English Channel consists of broad interfluves, sloping gently northwards, separated by dry valleys. This might be regarded as the dip slope of the cuesta formed by the Chalk, but this cannot be the case for the slope of the interfluves is not parallel to the dip of the Chalk (Fig. IX, 2). The surface therefore cannot be of structural origin but must have been cut by erosion across previously tilted strata.

Such summit surfaces are only the highest tread of the aptly named '*physiographic stairway*'. Lower treads may be shown by the bevelling of spurs. Many of the spurs projecting from both the North and South Downs into the Weald are bevelled or flattened at a height of about 200 feet above sea-level. The majority of these bevels are cut across beds of differing hardness but in a few cases they do coincide with the outcrop of a particularly resistant layer. Yet when this same bed outcrops at heights much above or below 200 feet, it does not produce a marked feature. Bevelled spurs at the same height can be found in the river gaps and also in some areas of the dip slope. They must be fragments of an erosion surface cut during a period of still-stand long enough for the base-levelling of the outcrops of the softer beds, but not sufficiently long enough for more than the notching of the more resistant Chalk. Some of the bevelled spurs are bare, on others there are spreads of solifluxion gravels and therefore the cutting of this 'platform' must ante-date a phase of periglacial conditions.

The lowest treads of the stairway are usually to be found within the valleys in the form of river terraces. Theoretically a terrace should be traceable continuously upstream from the raised beach, marking the sea-level to which the terrace is graded to a head of

rejuvenation at the limit of the subsequent wave of downcutting. All too often subsequent erosion has destroyed the raised beach and considerable stretches of the terrace. Sufficient however have usually escaped (Fig. V, 1) for the major episodes in the history of the river to be recognized.

The Recognition of Erosion Surfaces

The careful study of a contoured map is the first step in the recognition of erosion surfaces. Accordance of summit levels or the presence of platforms at lower levels can be inferred from the layout of the contours. These suggestions must be checked by more thorough methods. Carefully drawn profile sections (*see* Appendix I) will indicate the position of bevels more clearly, whilst comparison with a geological map will show whether such flattenings of the profile may or may not be due to structural causes.

A clearer picture is obtained by constructing *projected profiles.* A number of parallel sections are superimposed on the same base line, giving the effect of viewing the area from a considerable distance. The profile assumed to be nearest to the observer is drawn in full whilst only those parts of the more distant profiles which would not be concealed by higher ground are shown. This is a neater method than drawing all the profiles in full on the same base line to produce a composite profile. The eye is then rather confused by the variations in the depth of valleys. This is not significant, being arbitrarily determined by the way in which the regularly spaced section lines happen to cross the different valleys. Any platforms present are clearly visible on a projected profile and at the same time it can be seen whether the platforms are sensibly horizontal or whether they have a distinct slope.

Another method of map analysis is to draw *generalized contours* by joining the furthest point each contour extends down each interfluve. By thus eliminating the complications due to dissection by valleys, a picture of the general slope of the ridges is obtained. A platform will be indicated by a marked increase in the spacing of the generalized contours (Fig. IX, 1). This method is only applicable to a submature landscape with broad interfluves, for when Maturity is reached the interfluves begin to be lowered by valley widening and any bevels are destroyed.

Hypsographic curves show the percentages of the total area studied occurring between successive pairs of contour lines. These areas are determined either with a planimeter or by measuring the intercepts between the pairs of contour lines along a number of closely spaced

parallel lines across the area. If a smooth curve is obtained, similar in form to the thalweg of a graded river, the erosion of the area cannot have been interrupted by periods of still-stand. But any

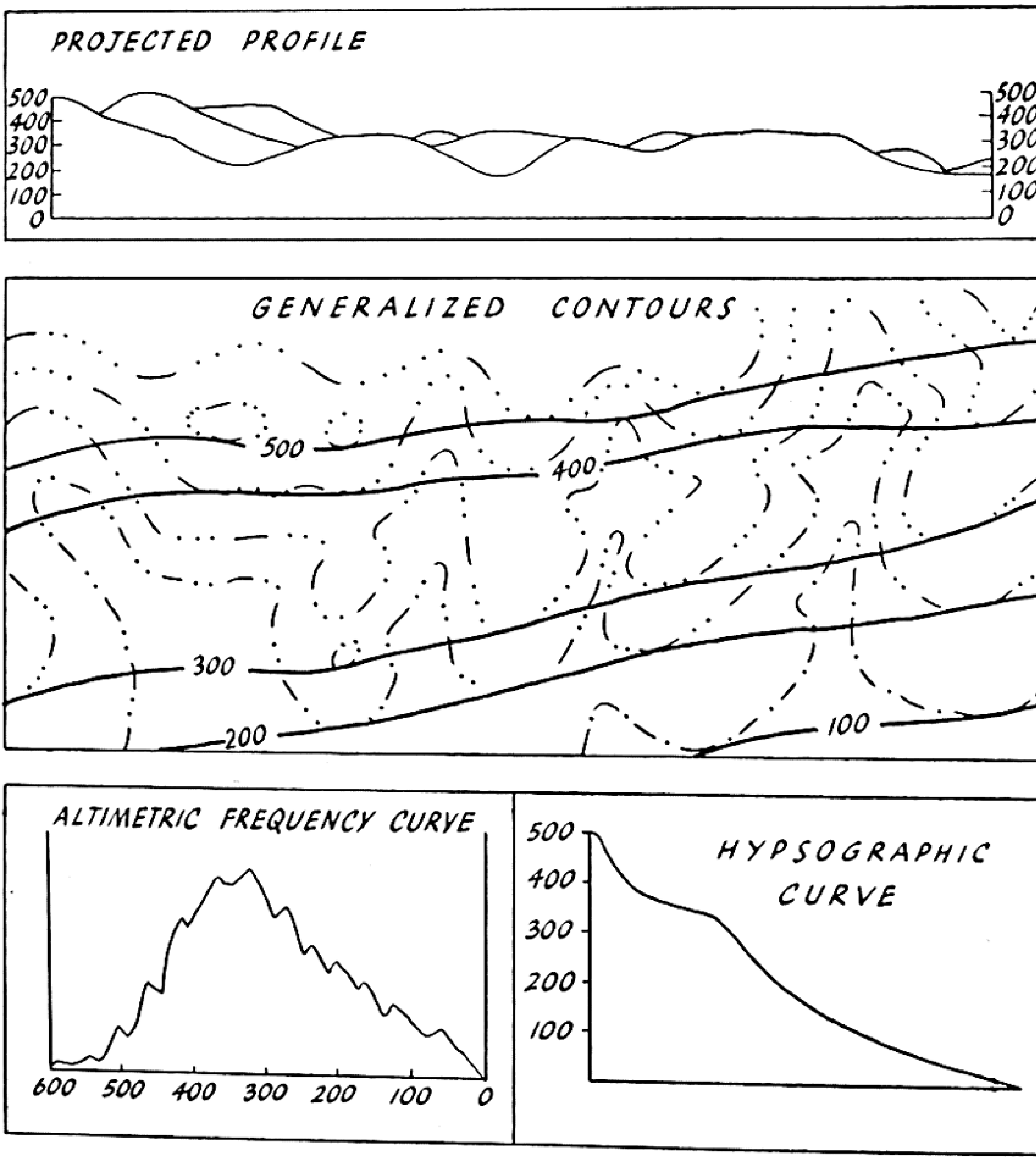


Fig. IX, 1.—A Platform just above 300 ft. O.D. Shown by Different Methods of Map Analysis

Note. In the middle diagram, the generalized contours are continuous lines, the surface contours dot-dash lines with their height in hundreds of feet above sea-level shown by the number of dots between each dash.

convexities on the curve indicate an excess of area at this height, an excess which is very probably due to bevelling.

If the map shows a large number of spot heights, places whose height has been accurately determined, counts of the number of

spot heights and summit points falling between different height ranges are very informative. Alternatively the map may be divided into small squares and the height of the highest point within each square estimated as accurately as possible. An *altimetric curve* can then be constructed by plotting the number of spot heights, etc., against altitude (Fig. IX, 1). Maxima on the curve indicate the height of summit plains and platforms.

The amount and quality of the information obtainable from a map are clearly governed by the vertical interval between the contours and also by the accuracy of contouring. There are three possibilities. The contours may have been carefully surveyed on the ground or they may really be 'form lines', which have been drawn to show the form of the ground though their height has only been estimated and may be inaccurate by a few feet or thirdly the contours may have been interpolated between spot heights in the drawing office without checking to see whether they really fit the ground. On the maps of the Ordnance Survey of Great Britain, the 50-foot contour and the contours at every 100 feet up to 1000 feet above sea-level and above that at 250-feet vertical intervals have been surveyed with great accuracy on the ground. But the intermediate contours are not so accurate either as regards true height or position, as may sometimes be proved by careful comparison of the map with the ground portrayed.

Map analysis therefore gives only a general indication of the position and height of erosion surfaces. A thorough investigation can only be made by walking over the ground, examining it from every angle and by determining the heights of any surfaces noted by reference to spot heights and the accurate contours or, if necessary, by using surveying instruments. Field work is particularly necessary in the study of river terraces, for the fragments left are often too small to be detected by map analysis alone, whilst the heights of those shown on a geological map may be rather uncertain. Accurate thalwegs of rivers cannot be drawn from maps, for the position of the intermediate contour crossings may be inaccurate and this will affect the slope of the curve. The height of the flood-plain or of the water surface, whichever is used, must be precisely determined at closely spaced points and this can only be done by survey on the ground.

Finally any deposits resting on an erosion surface or a surface formed by aggradation, such as a river terrace, may yield valuable information as to its age and conditions of formation. Their study is again a matter of field work. Precise and thorough field work is as

essential for geomorphological investigation as it is for any other branch of Geology.

THE ORIGIN AND DATING OF EROSION SURFACES

Erosion surfaces may be cut either by normal (fluviatile) or by marine agents. Theoretically the surfaces cut by marine erosion should be narrower than those due to normal erosion, for marine erosion slows down its own activities. As the belt of shallow water on the wave-cut platform and the wave-built terrace widens, the waves must break further offshore and therefore their erosive power will be reduced and the cliffs recede more and more slowly. There is no such check to normal erosion. The possible extent of a peneplain, the end stage of the normal cycle, is determined only by the size of the area whose base-level has remained stationary for a sufficiently long period.

A considerable positive movement of sea-level will cause the sea to spread or *transgress* across a land area, which may already have been nearly base-levelled by normal erosion. The work of the waves needed to trim off the upstanding areas to produce an extensive plain of marine erosion will have been very substantially reduced.

It is particularly difficult in the case of summit plains, of which only a few isolated fragments are left, to be sure whether they are due solely to normal erosion or to marine transgression. With erosion surfaces at a lower level the position may be easier. For example sufficient is left of the 200-foot surface which bevels the spurs of the Downs to show that this surface, the 'Ambersham level', must have originally extended right across the outcrops of the softer rocks which now form the strike vales of the Weald, whilst the harder rocks, which today form cuestas and ridges, were not base-levelled, but only slightly notched. The Ambersham surface must therefore have been cut, like the existing landscape, by normal erosion, for waves would have been unable to advance up through the narrow gaps in the Chalk cuestas and erode completely the softer rocks behind.

Any deposits resting on an erosion surface may show the method by which the final trimming, at least, was done. The spreads of sand and gravel found in places on the summit plain of the East Kent Downs have yielded the shells of marine organisms. The surface on which they rest, since uplifted to 550 feet above present sea-level, must therefore be a wave-cut platform. This surface can be traced westwards into Surrey, but there it does not extend to the edge of the escarpment as in Kent, but is bounded to the south by a change

of slope (Fig. IX, 2). This rise must mark the position of the old cliff line cut in the Chalk, but now so degraded after several million years of exposure that it is only recognizable by the trained eye, though its presence can be clearly shown by the drawing of generalized contours across the block of Downs between the valleys of the rivers Mole and Darent.

Level surfaces may be due not to erosion but to deposition. Exposures in the beds which underlie such flats will show whether they are formed by boulder clay or fluvio-glacial gravels or whether

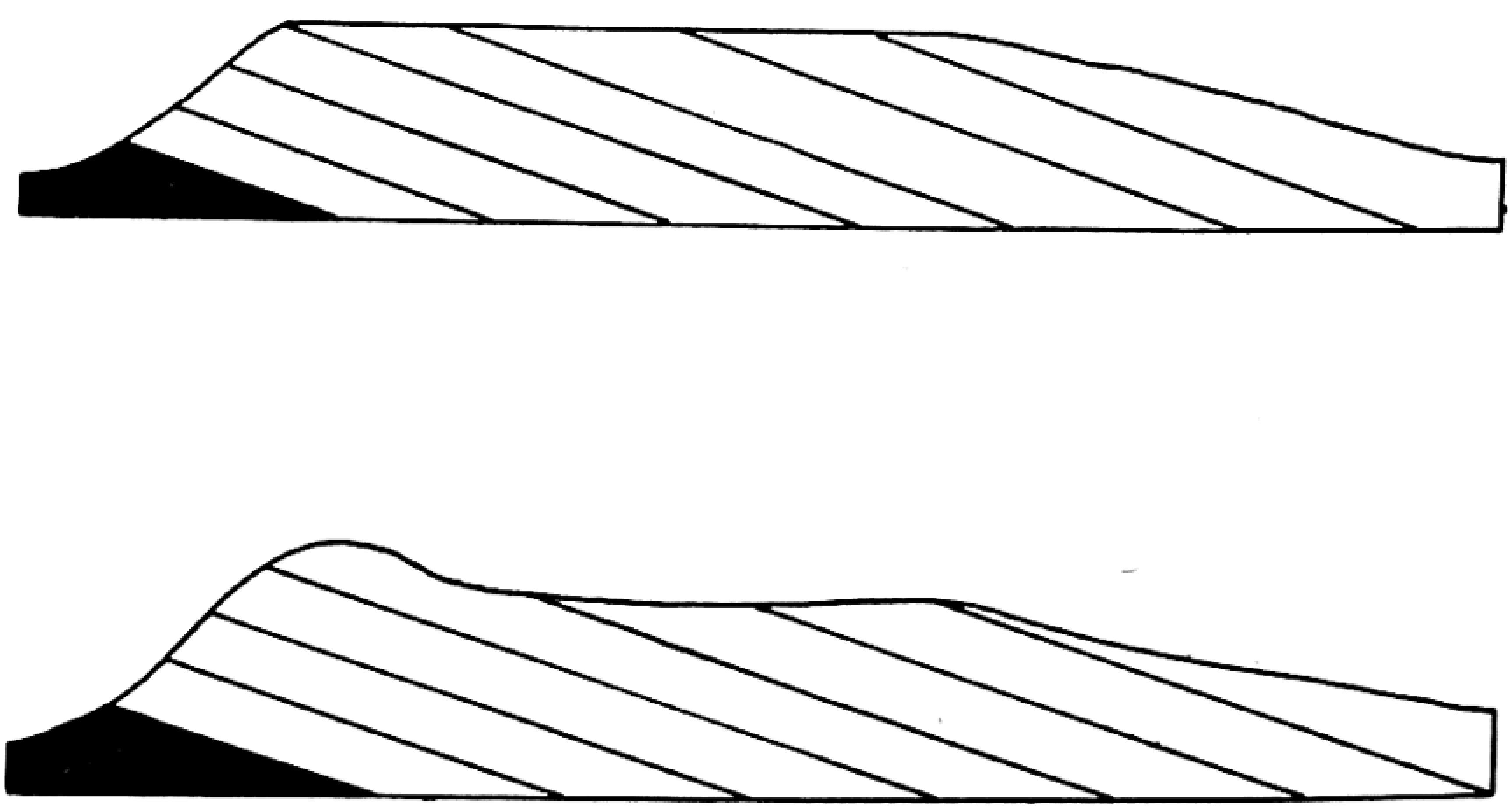


Fig. IX, 2.—Erosion Surfaces on the North Downs (after Wooldridge)

(*Above*) In East Kent, where the escarpment is bevelled.
(*Below*) In East Surrey, showing the degraded cliff line behind the crest of the escarpment.
The dip of the Chalk is indicated by the parallel lines.

they are river terraces or raised beaches with a veneer of beach shingle. In Chapter X are given those features of sands and gravels which indicate the conditions under which they were laid down and which must be sought to prove whether such a surface of deposition is due to glacial, fluviatile, etc., action.

The next problem is to date the surfaces found. In general, the higher and more dissected the surface the older it is, so the relative chronology within an area can usually be determined. But it is also desirable to establish the age of the surface in terms of the geological time scale described in Chapter XVI. This can only be done with certainty if deposits containing fossils rest on the surface. The central Wales summit plain is bare of deposits. A number of different views

have been expressed as to its age and how it was cut, but the problem is still unsolved. On the other hand the age of the East Kent summit plain is known within narrow limits from the fossiliferous deposits resting on it. There is admittedly always the possibility that the deposits on a surface may have been laid down some time after the cutting of the surface, but in the case of a transgressing sea the time gap is unlikely to be large. The Ambersham level of the Weald can be traced into Essex where it is overlain by boulder clay and in this case we have no direct evidence as to the time gap between the cutting of the surface and its burial beneath the ice. Again the surface on which a river terrace rests may have been cut during a phase of meander swing and then buried considerably later by a subsequent aggradation, so that there may be a considerable time gap between the surface of erosion beneath the terrace and the surface of deposition formed by the top of the terrace gravels.

But even a relative and not a completely accurately dated chronology for an area enables its denudation chronology to be reconstructed in fair detail. For example, the sea which cut the bevel at 550 feet on the North Downs, also covered the London Basin. Certain gravel-capped flats at a height of 400 feet in south Hertfordshire mark the next stage in the story. The gravels are of fluviatile origin and contain certain pebbles which must have come from the North Downs. Therefore the Thames must have been following a course well to the north of its present one, roughly along the line of the existing Vale of St. Albans and so into mid-Essex. The next major episode was the advance of the ice-sheets from the north-east across the Ambersham surface. Fragments of river gravels show that the Thames was then flowing between the high ground of Hampstead and Totteridge (Fig. IX, 3). But an arm of the ice-sheet filled up the eastern part of this valley and so the Thames was diverted southwards to lay down the Boyn Hill, Taplow and Flood-Plain Terraces to cut its Buried Channel and then to fill this during the last rise of sea-level (Fig. IX, 3).

The Correlation of Surfaces

Precise dating of erosion surfaces is particularly important when comparison is made of the sequence of two areas, separated perhaps by ground that has not been examined or ground too low for any higher surfaces to be preserved. If it is assumed that surfaces at say 800 feet above sea-level in the two areas must be part of one surface, because they are the same height above the present sea-level, this implies that it is sea-level which has dropped whilst the land areas

have remained relatively stable. But there is always the possibility that surfaces may not be horizontal but may have been warped

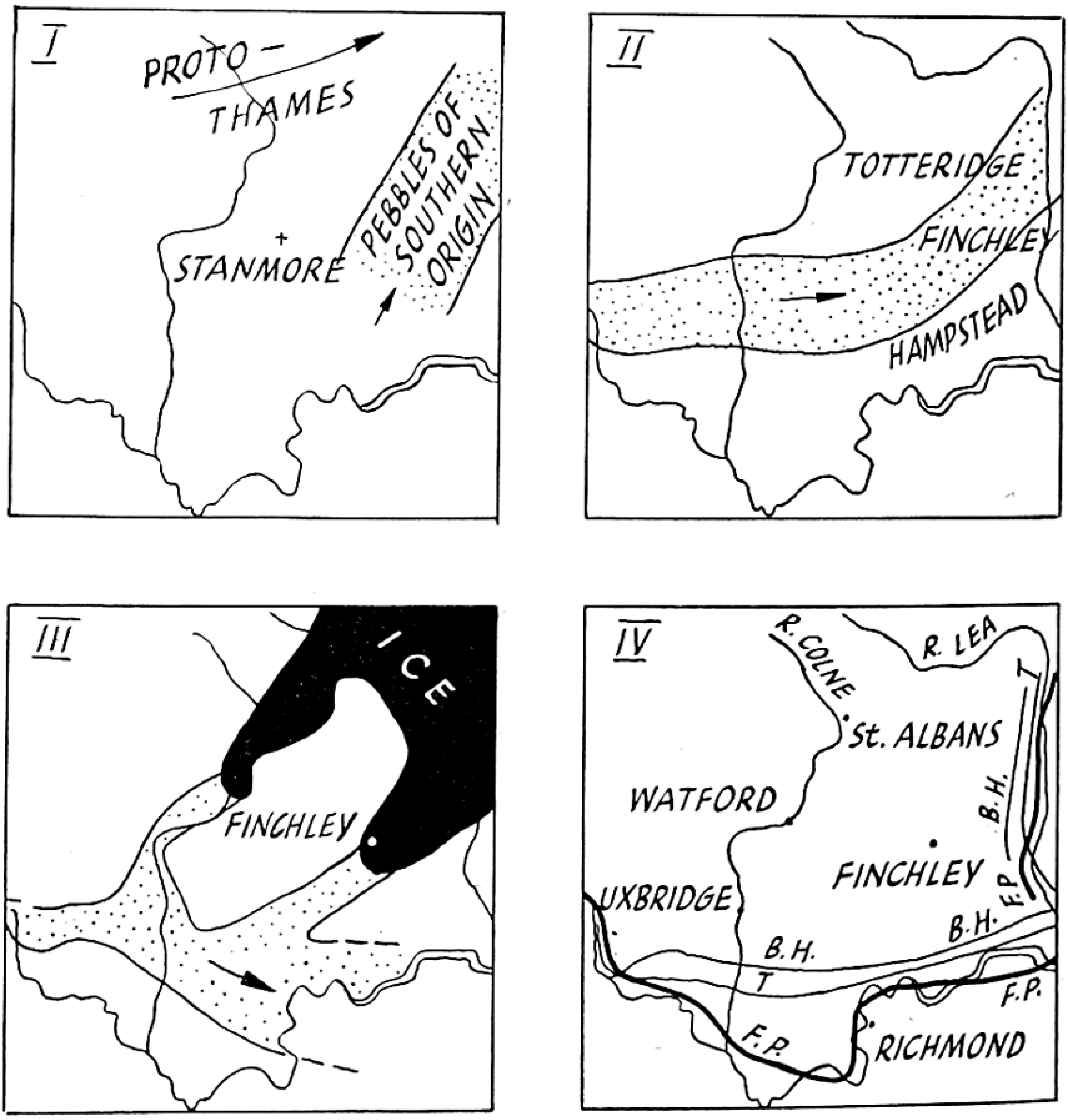


Fig. IX, 3.—The Changes in the Course of the River Thames (after Wooldridge)

I. 400 ft. Gravel Stage.
II. Course before the advance of the ice-sheet.
III. The River Thames diverted south of the Hampstead Ridge by the blocking of its pre-glacial valley.
IV. The course of the River Thames at:
B.H.: Boyn Hill Terrace level.
T.: Taplow Terrace level.
F.P.: Flood-Plain Terrace level.

by either isostatic or tectonic movements at some period since their formation. If this has occurred, two such widely separated surfaces will not be of the same age though they are at the same height. If

the two surfaces cannot be dated by fossil evidence we must consider their relation to other surfaces. If the several treads of the physiographic stairways of the two areas are spaced similarly and at corresponding heights, both areas must have been affected by the same periods of still-stand and therefore correlation by height alone is justified.

Alternatively when a surface can be traced continuously over a considerable distance, any marked variation in its height must be due to subsequent warping. An exception, of course, is the normal rise upstream of a river terrace. The Ambersham level, for example, slopes steadily downwards from the height of 200 feet as it is traced into East Anglia, an area which is known from other evidence to have been appreciably downwarped in recent geological times. The tracing and correlation of erosion surfaces is therefore an important means of delimiting those areas which have remained stable and have been affected by eustatic change of sea-level from those which have been subjected to isostatic or tectonic movements.

SECTION C

Petrology and Mineralogy

CHAPTER X

Conditions under which Rocks and Minerals are Formed

THERE are three main groups of rocks, Sedimentary, Igneous and Metamorphic (Fig. II, 10).

Sedimentary Rocks were formed by the deposition, in the depressions of the Earth's crust, of the products of the weathering of pre-existing rocks. Weathered rocks were broken down into fragmentary material and soluble compounds. The latter could be transported only in water, the former by moving water, by ice, by the wind or by gravity-slip. Rock fragments were deposited wherever the energy of the transporting agent fell below a critical value. The larger the fragments, the higher this value and therefore the coarser-grained rocks, containing boulders and pebbles, were deposited nearer the place of weathering than finer-grained types like sands and clays. The material removed in solution might be deposited either as a chemical precipitate or it might be secreted by organisms to form their skeletons.

The distinctive features of sedimentary rocks are:

(i) they are usually well stratified; the planes of stratification being due to slight changes in the conditions of deposition,

(ii) they often contain fossils; indeed, some sedimentary rocks are composed almost entirely of the remains of organisms.

Igneous Rocks, on the other hand, were formed by the consolidation of molten rock material (magma) either on or beneath the Earth's surface. When the magma cooled to a certain temperature crystallization or the formation of minerals began. If cooling was slow, the individual minerals grew to a considerable size before solidification took place and a coarse-grained rock was formed. But if cooling was rapid, the magma solidified before the minerals had

grown appreciably and a fine-grained rock or, with exceptionally rapid cooling, a glass was formed.

Igneous rocks differ from sedimentary rocks in their crystalline nature by not containing fossils and by usually being unstratified. Certain igneous rocks do, however, show a crude type of stratification, due to joint planes developing, during cooling, parallel to the top and bottom surfaces of concordant intrusions or the upper surface of a discordant intrusion. Well-marked joints are also often developed at right angles to these surfaces.

Mineral Deposits are concentrations of minerals of economic value. Whilst some of them are of sedimentary origin and will be described with the sedimentary rocks, the majority of mineral deposits are of igneous origin and have consolidated under rather special conditions.

Metamorphic Rocks were formed from either sedimentary or igneous rocks by the action of great pressure and high temperatures aided by the attack of gaseous fluids circulating through the rocks. As a result the mineralogical nature and, if much new material was added, the chemical composition of the original sedimentary and igneous rocks was changed. New minerals, often of high density and therefore occupying less volume, were formed, whilst the original structures of the rocks, including any fossils, were obliterated.

Metamorphic rocks are recognized by the presence of a distinctive suite of minerals, together with characteristic structures such as cleavage or schistosity or by having a toughened, fine-grained appearance when fusion of rock material has occurred.

SEDIMENTARY ROCKS

The majority of the material worn away from the land areas is deposited in the ocean basins. According to the conditions of deposition and the nature of the material laid down, a number of sedimentation zones can be recognized (Fig. X, 1). In the *littoral zone*, between tide marks, the sediments are thin, for they are constantly being worked over by the waves and all material beneath a certain size is carried out to sea. Beach shingle with its well-rounded and battered pebbles is typical of this zone but sands and even muds can form in sheltered areas to which little coarse material is transported. The littoral zone of modern beaches is usually a few hundred yards or less in width, but exceptionally, as in the Bay of Fundy and Hudson Bay, it may widen to several miles. At times, however, during the geological past, the littoral zone may have been

many times wider, on the average, than it is today, for the present relief of the World is abnormal, owing to the recent glaciation and the preceding mountain building phase. During the long periods between the major mountain building episodes, the continental masses must have been extensively peneplained and their margins flooded by shallow seas, similar to Hudson Bay. Lyell's dictum that 'the Present is the Key to the Past' is valid in explaining many of the minor features of rocks, but the environments in which sedimentary rocks are being formed today may not be typical of nor include all those of the geological past.

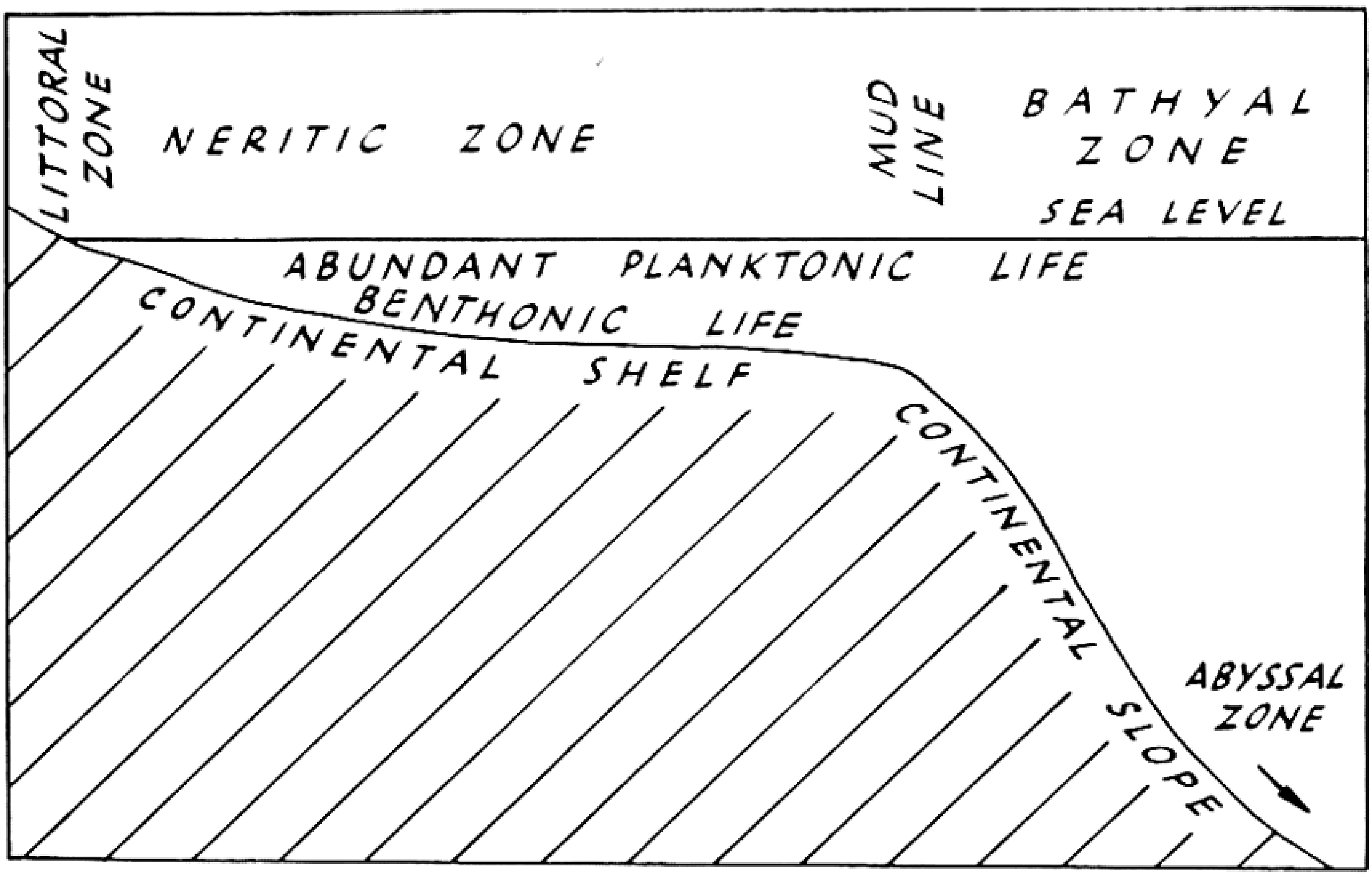


Fig. X, 1.—Zones of the Continental Margins

The *neritic zone*, lying seaward of the littoral zone, is often hundreds of miles in width, for it covers the *continental shelf*. A great variety of deposits is laid down on it—sands and gravels in areas of strong wave or current action, muds in quieter regions and, more locally, accumulations of organic remains, such as the coral reefs of the tropics and the oyster banks of more temperate waters. The areas in which the different kinds of sediments are deposited are not sharply defined but grade into one another, so that when we examine uplifted portions of former neritic zones, we may find limestones in one area and as these are traced in a certain direction, they may become more and more sandy and finally pass into sands. In general, the coarse-grained sediments are laid down nearest to the land but

increasing knowledge of the deposits now forming on the continental shelves shows that there are many areas with muds forming close inshore and sands further out. This is particularly the case near the estuaries of rivers, where reaction with the salts in the sea water causes *flocculation* of the clay particles of the suspension load of the rivers. The particles join together to form compound grains which settle to the bottom. If bottom currents are weak or flocculation extremely heavy, much of this clay may accumulate, but in regions of greater current and wave activity, the clay particles will remain in suspension and will finally be swept out into deeper water.

The neritic zone, particularly its shallower portions, is the region of greatest abundance of marine life. The waters are usually well oxygenated, food is abundant, so that *benthonic* or bottom-living forms, such as oysters, corals, sea-urchins and starfish, etc., can flourish, whilst in the waters above are myriads of other creatures, either *nektonic* or swimming forms, like fish, or drifting or floating *planktonic* forms, like jelly fish and the larval stage of many benthonic creatures. The remains of these organisms may be buried in the sediments and preserved as fossils.

At the 'mud line', at a depth of about 100 fathoms, towards the edge of the continental shelf, the varied sediments of the neritic zone pass gradually into the much more uniform deposits of the *bathyal zone*. For a considerable distance down the continental slope, only muds, formed of the finest-grained terrigenous or land-derived material, are accumulating. Benthonic life is less varied and numerous than in the neritic zone, but planktonic and nektonic life is usually abundant in the waters above, especially in the zone of light of the highest 30 fathoms.

As the supply of terrigenous material gradually decreases, the remains of planktonic forms make up a greater proportion of the sediments. At a depth of about 1000 fathoms, the bathyal zone grades into the *abyssal zone* of the deepest parts of the oceans. Between 1000 and 4000 fathoms, the abyssal deposits consist of soft oozes, formed of the myriads of minute plantkonic creatures, which secrete skeletons made of either calcium carbonate or of silica. Again there is a zonation, with the calcareous oozes composed of foraminifera (p. 238) and the lime-secreting algae (p. 247), accumulating in less deep water than the siliceous oozes, composed of the remains of radiolaria (p. 238) and diatoms (p. 236). The calcareous skeletons are more easily dissolved than the siliceous ones, as they sink slowly downwards through the cold waters of the abyss. But at depths greater than 4000 fathoms, even the siliceous skeletons have passed

into solution and in the deepest parts of the oceans only Red Clay is accumulating, composed of the very finest wind blown dust, in which are small nodules of manganese dioxide and the earbones and teeth of whales and sharks.

The abyssal deposits cover considerably more than half the total surface of the Earth, but they seem to be unrepresented in the sedimentary rocks now exposed on the continents; a strong argument for the ocean basins having been permanent features of the earth's crust (p. 225).

TERRESTRIAL

On the land areas sedimentary rocks are being formed beneath and around glaciers and ice-sheets, in deserts and intermontane basins, on the flood-plains of rivers, in lakes and in swamps. There is a marked difference in the degree of sorting and the rounding of the fragments according to whether or not they have been transported by water and wind.

Deposits of *glacial* origin are typically unsorted, with angular, facetted and striated erratics, which usually include a wide range of rock-types. They grade away from the ice-sheets into a wide zone of *fluvio-glacial* deposits, which have been worked over by melt waters. With increasing distance from the ice front, *fluvio-glacial* deposits become better sorted, striations are worn off the erratics, which become more rounded in shape, whilst the range of rock-types present is rapidly reduced, for only the hardest ones can survive the repeated battering that occurs in fast-flowing water.

True *fluviatile* deposits are, therefore, characterized by a high degree of sorting and a limited range of constituents, whilst in the lower reaches of rivers, where the water is flowing less swiftly, fine-grained sands, silts, and even muds may be deposited.

Aeolian deposits are usually very well sorted and rounded, whilst any pebbles lying on the surface will be smoothed and polished by the driven sand and will acquire the distinctive dreikanter shape. Wind blown sands are often strongly current-bedded with a greater variation, both in the amount of slope and the direction of the foresets (p. 23) than in water laid deposits (Fig. X, 2).

The screes that mantle the lower slopes of the mountain rims of intermontane basins are composed of ill-sorted angular material. The rock-types present are all of local origin and do not include the far travelled types found in glacial deposits. As the scree slides slowly downwards the fragments become more rounded, smaller in size and somewhat better rounded and the talus fans often coalesce to

form a bajada. Occasional rainstorms will further wash and sort this material, whilst in the central parts of the larger basins, wind action may be important and the pediment belt grade into a zone of sand dunes, surrounding a lake, the extent of which varies with the spasmodic rainfall and, perhaps, snow melt, on the mountains.

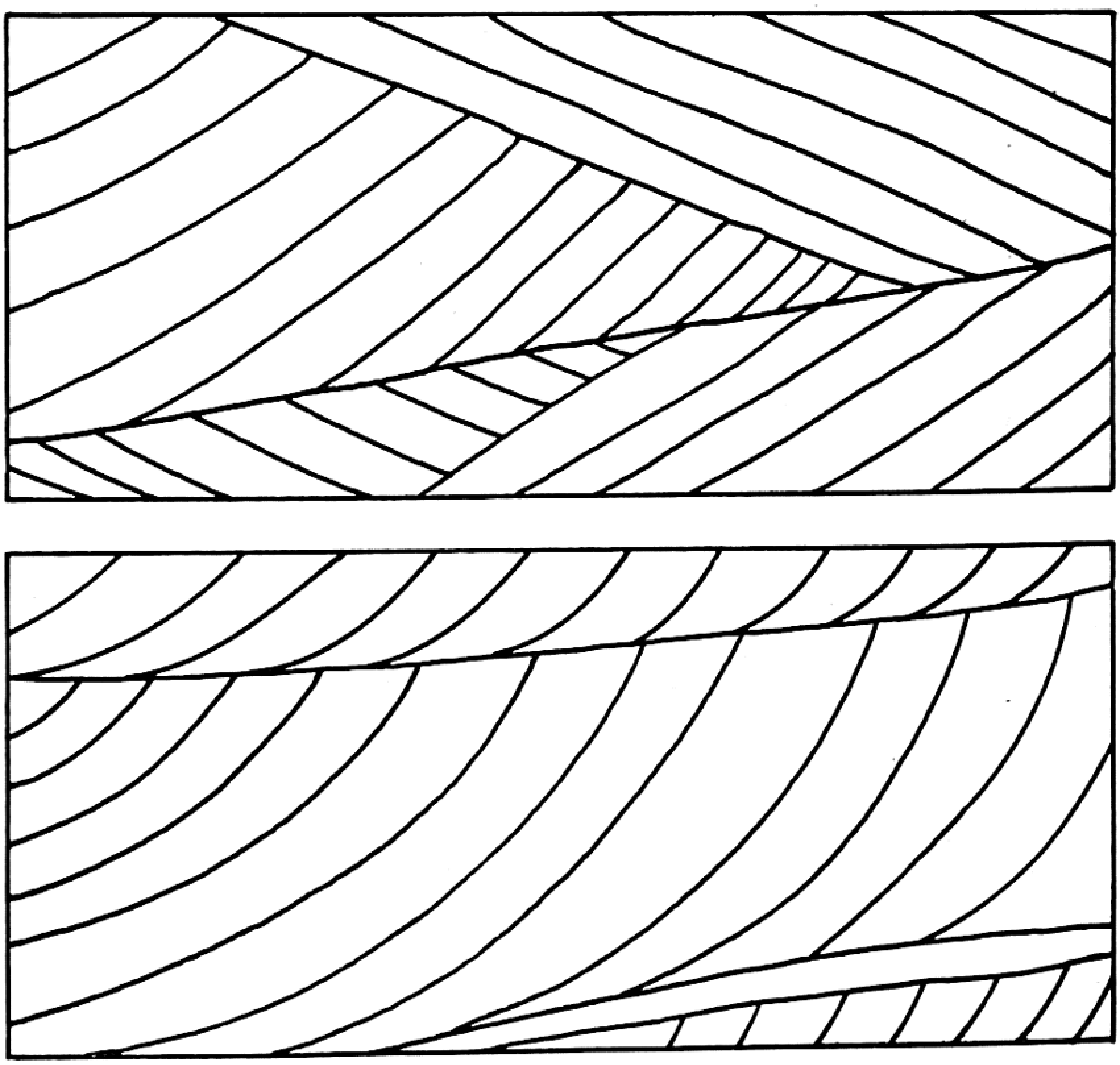


Fig. X, 2.—CURRENT-BEDDING
Wind deposited sands (*above*) and water laid sediments (*below*)

The deposits laid down in the more permanent *lake* basins, in regions of more regular rainfall, consist of a marginal zone of sand or even gravel, grading into muds, which often contain much organic matter, composed of planktonic, nektonic or benthonic organisms or of vegetation, that has floated into the lake and sunk when waterlogged.

Fossils are much rarer in terrestrial than in marine deposits. In the first place the glacial, periglacial, desert and intermontane regions

contain little life, and even on the flood-plains of rivers, where life is usually abundant, the chances of its being preserved before decomposition sets in are much less than in the seas.

Terrestrial deposits, mainly of organic origin, are however formed in *swamps*. The slow-flowing rivers deposit much mud and the mud flats or the sand flats formed by occasional floods may be covered by luxuriant vegetation, below which is forming a layer of peat.

So far we have treated rocks of marine or terrestrial origin as separate entities, but if the shore line fluctuates in position, different types of deposit will interdigitate (Fig. X, 3). This is particularly the

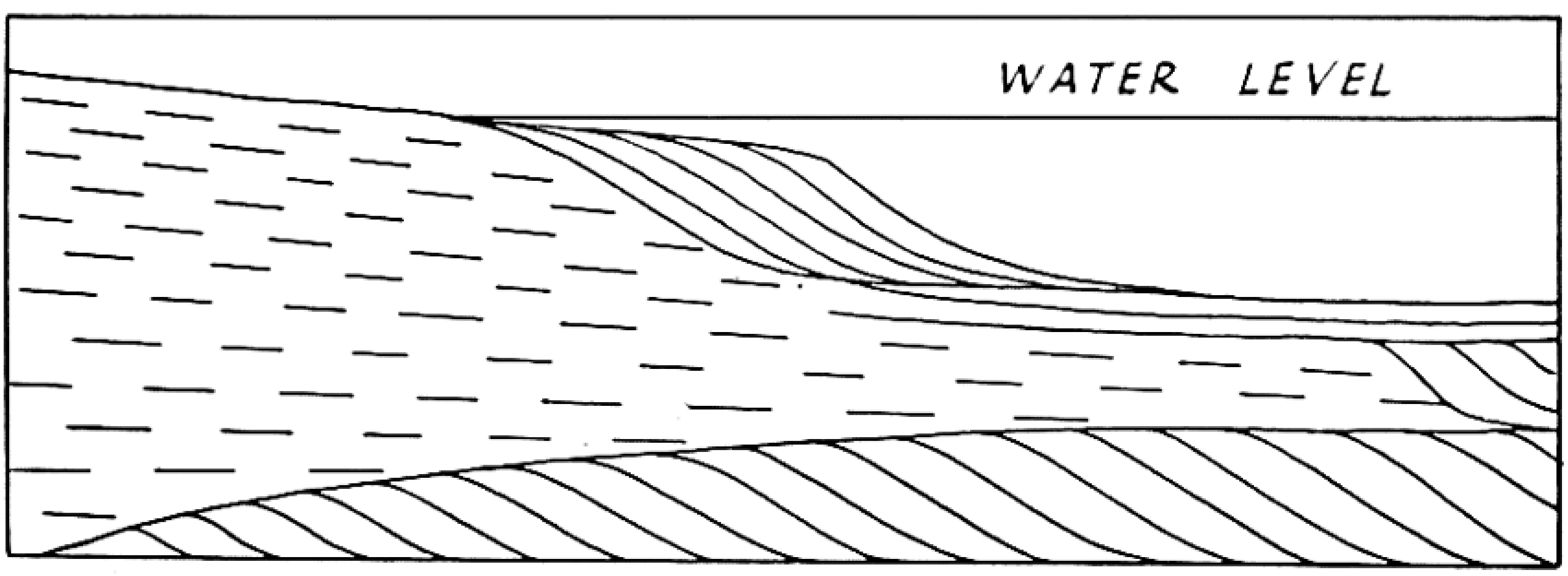


Fig. X, 3.—Diagrammatic Section of a Delta

The subaerial topset beds (broken lines) interdigitate with subaqueous foreset beds (current-bedded) and bottomset beds (continuous lines). The shore line first moved seawards, then retreated landwards and is now moving seawards again.

case in *deltas*, built out by rivers into seas or lakes. The exposed or subaerial surface of a delta, really a greatly expanded flood-plain with scattered lakes, ponds or swamps, marking the site of partly silted up distributaries, slopes gently into the subaqueous portion, consisting of a belt of topset beds with current-bedded foreset beds along the growing front of the delta and these pass into the bottomset beds, which are normal marine or lacustrine sediments. Any variation in the level of the water will produce on such a gently sloping surface great shifts in the position of the shore line. In fossil deltas, it is often difficult to prove that such oscillations of sea-level and interdigitations have occurred, for the deposits laid down on the exposed surface of the delta may vary little in appearance from those deposited under water. Even if fossils are found, they may be of doubtful value, for trees, the bodies of animals, even the empty

shells of land snails, or shells attached to driftwood, may be swept far from the land, before they sink to the bottom, whilst marine creatures like porpoises, dolphins and whales may swim up a river and then become trapped and buried.

IGNEOUS ROCKS

The igneous rocks are formed either by the *extrusion* of magma on to the Earth's surface from volcanoes or fissures or by the *intrusion* of magma into the rocks of the Earth's crust.

The Extrusive Igneous Rocks

Volcanoes are formed by magma rising from the deeper parts of the Earth's crust to the surface. The magma may issue as lava, or if it is viscous and blocks the vent, the pressure of the gases beneath may be sufficient to cause explosions, blowing out showers of volcanic debris and forming fragmental rocks, which though of igneous origin, often resemble certain sediments in their minor structures and hence are known as the *Pyroclasts*.

A volcanic cone composed of a mixture of lava and pyroclastic material is built up round the orifice, often very quickly. In February 1943, a farmer ploughing near the village of Paracutin, in western Mexico, noticed steam issuing from cracks in the ground. A few days later there was an explosion, followed by others. The new volcano grew rapidly, reaching a height of 550 feet in a week, and after four months the cone was over 1000 feet in height and about 3000 feet in diameter at its base, whilst the lava flows from it had reached and engulfed the village and the showers of ash had devastated the country-side for miles around. Eruptions continued for some years and then gradually ceased, so that the volcano, if not extinct, is now at least dormant.

Volcanoes of this type, which have developed round a pipe-like conduit, are known as *Central Volcanoes* and are classified into the following groups, according to the nature of the volcanic activity and the form of the cone produced:

A. Lava Volcanoes:
- (i) Hawaiian type;
- (ii) Strombolian type.

B. Explosive Volcanoes:
- (iii) Vesuvian type;
- (iv) Pelean type.

The *Hawaiian type* is built up of sheet after sheet of lava with occasional thin layers of pyroclastic material. As the lava is relatively

fluid, the cone has gently sloping sides. The molten lava issuing at temperatures above 1000°C. is quickly chilled. According to whether the gases in the congealing lava escaped in sudden bursts or quietly, the upper surface of the flows show either a blocky (aa) or a ropy (pahoehoe) structure.

Volcanoes of this type form the greatest mountains on the Earth. Mauna Loa in the Hawaiian Islands rises over 30,000 feet above the

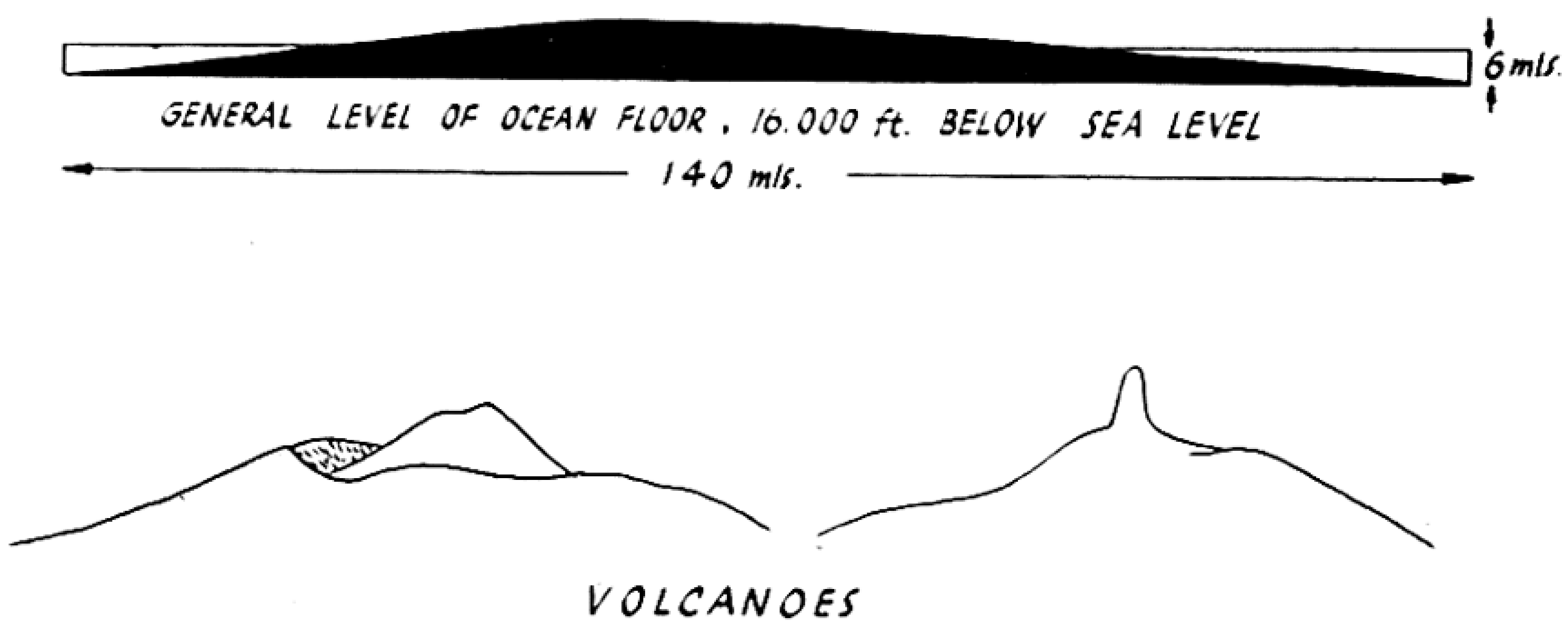


Fig. X, 4.—VOLCANOES

Above: A true-scale section across Mauna Loa, Hawaii.
Below, left: Vesuvius, showing the cone that has been built up within the great crater formed when the top of the mountain was blown off in A.D. 79.
Below, right: Mt. Pelée, in Martinique, showing the spine that protruded to a height of 900 feet after the eruption of 1902.

flat floor of the Pacific Ocean, though only the upper half of this great pile, which is 70 miles in radius at its base, is above water (Fig. X, 4).

Volcanoes of the *Strombolian type* are formed of rather more viscous lava, so that pyroclasts are more prominent. Stromboli, to the north of Sicily, has been in eruption throughout historic times; slight eruptions of ash and stones taking place every few minutes, whilst at night the lava bubbling in the throat of the volcano lights up the steam cloud that hangs over the mountain, which has been called "the lighthouse of the Mediterranean".

In the *Vesuvian type* explosions are spasmodic but very violent. A long period of quiescence is succeeded by intense activity, when much of the upper part of the cone may be blown into the air (Fig. X, 4). Vast quantities of gas and steam are released, forming a cloud extending upwards for several miles, whilst the ash may be carried considerable distances by the winds. The towns of

Pompeii and Herculaneum were overwhelmed in A.D. 79 by explosions of this type. Both during the short spells of explosive activity and during the longer spells of relative quiescence, flows of very viscous lava break out from fissures in the sides of the mountain.

In the *Pelean type*, the lava is so viscous that it completely blocks the upper part of the vent. The gas-rich and highly compressed magma beneath escapes, at intervals, by forcing open fissures in the sides of the cone. *Nuées ardentes* or gas clouds, highly charged with fragments of incandescent lava, may escape from the fissures. In 1902 a nuée ardente from Mt. Pelée in the Island of Martinique swept down on the town of St. Pierre, asphyxiating 30,000 people in a few minutes and causing the sea to boil, so that many ships in the harbour were sunk. Shortly after this the plug of lava in the neck was forced upwards to form a spine, 900 feet in height, which, however, soon crumbled away, owing to the attack of hot gases at its base and the weathering of its upper part.

Whilst very different forms of cone (Fig. X, 4) are built up by these several types of activity, an individual volcano may pass through an alternation of Vesuvian and Pelean or other phases.

Volcanoes are rarely perfect cones, more often the apex is missing. Fujiyama in Japan, which figures in so many paintings, is one of the exceptions, being a beautifully symmetrical conical mountain. In many volcanoes the apex of the cone has been blown away, leaving a more or less circular *crater* rimmed with cliffs of lava or pyroclastic material. If the volcano is active, the bottom of the crater is filled with molten or semi-congealed lava but in a long dormant or extinct volcano the plug has completely solidified and the crater is often occupied by a lake. If the volcano becomes active again, the waters of this lake will be ejected from the crater and will wash the unconsolidated pyroclastic material down the sides of the cone as a destructive 'mudflow'. In Java in 1919, a disaster of this type killed 5000 people and destroyed or partly destroyed nearly 100 villages; inhabited by farmers cultivating the very fertile soils which develop on weathered volcanic rocks.

But in many of the larger volcanoes, the active cone is in the middle of a great depression or *caldera*. The extinct Crater Lake Caldera in Oregon is $5\frac{1}{2}$ miles in diameter with vertical sides rising, in places, 2000 feet above a lake 2000 feet in depth. Calderas were once thought to be the stumps of volcanoes left after great explosions had blown away most of the cone. But in several cases, it has been shown that the quantity of pyroclastic material lying round the caldera is not nearly sufficient to reconstruct the cone. It is therefore

clear that another mechanism is needed. The *explosion-collapse* theory explains the formation of calderas by first an explosive phase, during which so much magma was ejected that the roof of the magma chamber was left unsupported and this collapsed to produce the caldera (Fig. X, 5).

Not all volcanic outbursts occur on land. The Hawaiian and many other islands have been built up by successive eruptions,

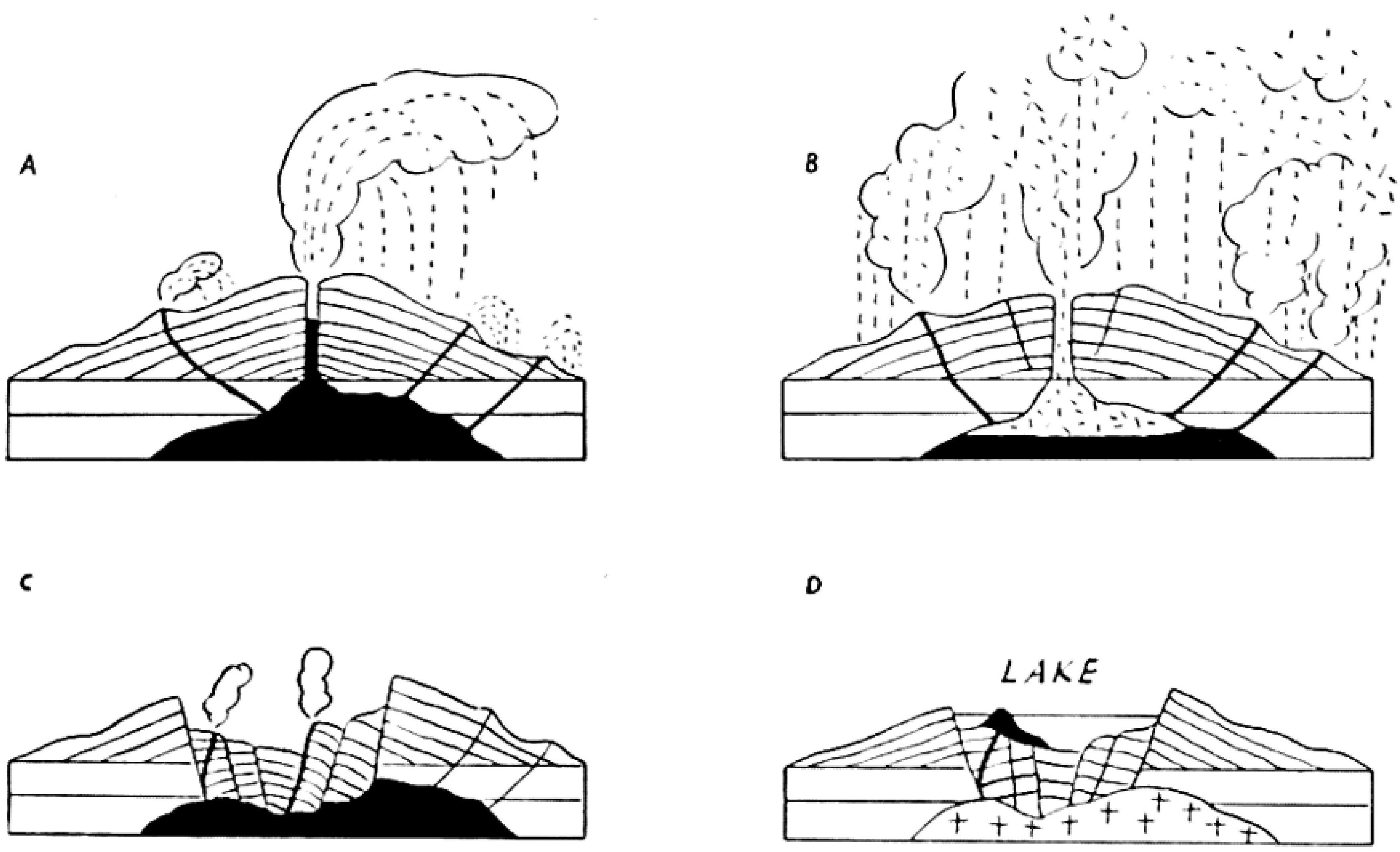


Fig. X, 5.—History of the Caldera at Crater Lake, Oregon (after H. Williams)

A. Early stages of eruption.
B. Great explosive eruptions with the cone beginning to collapse.
C. Caldera formed by the collapse of the cone into the magma chamber.
D. The caldera now occupied by a lake, in which are minor volcanic cones formed during the waning of activity. The magma chamber has consolidated.

submarine at first, subaerial later. Submarine eruptions of the explosive type produce great so-called 'tidal' waves, which may cause grievous loss of life. Great waves are also produced by explosive eruptions on islands. The best known example was that of Krakatoa, an uninhabited island off Java, in 1883. A most violent series of explosions blew away nearly the whole of what had been believed to be an extinct volcano. The noise of the explosion was heard 3000 miles away, the seas around the island were covered with great masses of floating pumice (the frothy top of lava flows), whilst the

enormous quantity of dust thrown out darkened the sky over a much wider area and was eventually carried by the upper winds right round the Earth. Great waves broke on the neighbouring coasts, washing away buildings fifty or more feet above normal sea-level, carrying ships nearly two miles inland and leaving them stranded thirty feet above sea-level, and drowning 36,000 people.

Submarine lava extrusions are fortunately not so devastating. They produce a characteristic form of lava, *pillow lava*, consisting of flattened ellipsoidal masses about the size and shape of an ordinary pillow. The outer surface of the pillows is very fine-grained, owing to the very rapid chilling by the water, but the centre of the pillow is crystalline. The formation of such pillows has been observed several times, when aa or pahoehoe lava flows into water. The spaces between the pillows are filled either with pyroclastic or sedimentary material. Fossil pillow lavas are easily distinguishable from flows of subaerial origin, which are often massive in structure and may show weathered upper surfaces or 'boles' composed of lateritic material.

Fissure Eruptions with the magma issuing from a number of parallel fissures are another form of extrusion. The very fluid lava spreads out as sheets, first filling up any irregularities and then extending horizontally. Lava is resistant to normal weathering and hence the term *Plateau Basalts*, from the nature of the rock and its topographic expression, is often applied to the products of fissure eruptions. The edges of the plateau and the sides of the valleys cut through it usually appear terraced, for the plateau is built up of numerous horizontal flows, each of which has a massive lower portion, forming a line of crags, whilst the pumaceous, and therefore more easily weathered upper part, forms a grassy slope.

The quantity of lava extruded in this way is enormous. In Iceland in 1783 about three cubic miles of lava issued from a single fissure twenty miles in length and spread over more than 200 square miles. Many fossil examples, composed of numerous flows, are far more extensive. It is nearly a morning's drive from Belfast to the Giant's Causeway across the Antrim Basalt Plateau, whilst the Snake River Basalts in the United States cover 200,000 square miles and the Deccan Traps of India a comparable area.

The Intrusive Igneous Rocks

The volcanic are the only kind of igneous rocks which we can study in the process of formation today and they provide much information as to the genesis of igneous rocks in general. Reference has already been made (p. 15) to the manner in which the real

origin of igneous rocks was proved by the study of recent and fossil volcanoes.

Active volcanoes demonstrate the extrusion of lava and the formation of pyroclasts, whilst eroded volcanoes reveal deeper-seated structures. The pipe of an eroded volcano of the central type is composed of a more or less circular mass of fine-textured rock. Such volcanic *necks* or *vents* are often very resistant to weathering and form steep-sided hills like the Castle Rock, Edinburgh, or the Bass Rock off the nearby coast.

At Glencoe in western Scotland is exposed a *ring complex*, consisting of circular ring-dykes, which are believed to have risen up the fractures formed by the 'cauldron subsidence' of a large caldera (Fig. X, 6).

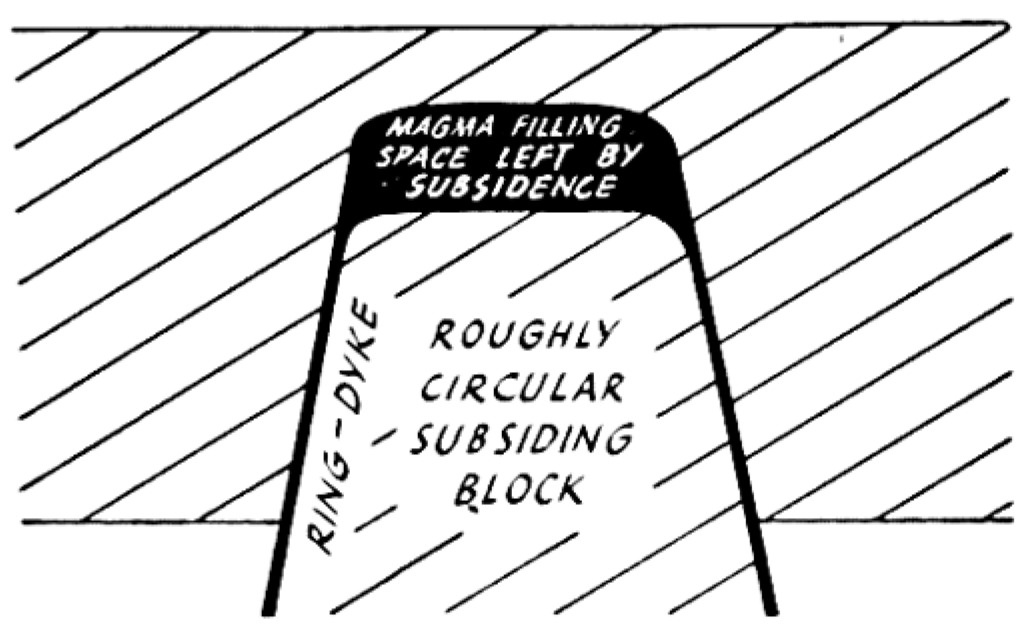


Fig. X, 6.—Diagrammatic Section to Show the Emplacement of a Ring Complex as a Result of Cauldron Subsidence

Many lava plateaux are intersected by swarms of parallel, more or less vertical, *dykes* of fine-textured igneous rock. They are clearly the fissures up which the magma rose.

If we apply the general principle that the texture of an igneous rock indicates its cooling history we can explain *sills* intruded along the bedding planes of rocks. Sills often have the same texture as the central parts of massive lava flows and therefore cannot have been formed under any great thickness of cover. Sills, however, differ from lava flows in the character of their upper and lower surfaces. In sills both are fine-grained, perhaps even glassy, showing that the magma was intruded into cold rock but in lavas only the base shows such signs of chilling whilst the upper part is pumaceous or may have been weathered into bole.

If an igneous rock contains large crystals (*phenocrysts*) of one or more minerals in a fine-grained ground mass, we must infer two

stages of cooling. First the slow growth, at a considerable depth, of the phenocrysts and then, before consolidation was completed, the extrusion or intrusion of the magma to a higher level, so that the remainder of the magma consolidated very quickly.

Rocks which are uniformly coarse-grained, must have cooled very slowly. But sometimes, as in the Bushveld Complex of South Africa, intrusions showing this type of texture are layered, with the minerals of the highest density concentrated in the lowest levels. Such *differentiation* is explained by supposing that the minerals of highest density were the first to crystallize and that they sank through the still liquid portions of the magma, which formed rocks of lower density on consolidation. The change from one layer to another is usually a gradual one. We cannot therefore regard the formation of such a differentiated complex as due to *multiple intrusion*, that is, to the intrusion of successive bodies of magma of slightly different chemical composition. *Composite dykes* showing sharp contacts between the different rock-types are examples of multiple intrusions, for the first magma had consolidated before the intrusion of a different magma along the same line of weakness.

Batholiths, the discordant intrusions, composed of coarse-textured, more or less equigranular granitic rocks, give rise to special problems. Batholiths are often of enormous size, the Coast Range Batholith of British Columbia being 1250 miles in length and 125 miles in width. They occur in areas of intensely folded and often regionally metamorphosed rocks and it is clear that the great orogenic or mountain-building movements usually culminated in the formation of batholiths. The granitic rock is clearly of *plutonic* origin, that is, it has been intruded at considerable depth. The question at issue is the manner of its emplacement.

One school of thought believes that granitic batholiths have originated from great bodies of molten magma which have forced their way upwards, displacing the rocks in their path. In Jersey, the roof of a batholithic mass is exposed, showing the magma frozen in the act of *stoping* its way upwards (Fig. X, 7). Tongues of granitic rock can be seen penetrating the fissures of the country rock and wedging off large blocks or *xenoliths*, which are completely enclosed by granite. As the xenoliths sank into the magma, they were gradually absorbed and eventually, at a considerable depth below the contact, all trace of xenoliths is lost. But the incorporation of country rock must have changed the chemical composition of the magma by *assimilation* and round many of the xenoliths is to be found a skin of a hybrid rock, more or less intermediate between the granite and the

country rock. Whilst the upward movement of granite by stoping has been clearly demonstrated, the larger problem, the space problem, of what has become of all the country rock displaced, is still unanswered. Can it all have been assimilated by the advancing magma?

There are those who believe that the space problem is solved if batholiths were formed not by displacement but by replacement. Instead of molten magma forcing its way bodily upwards, they picture gaseous liquids rising from depth and so thoroughly permeating the country rock that it is gradually altered into granite.

Fig. X, 7.—GRANITE (WHITE) STOPING ITS WAY INTO COUNTRY ROCK (STIPPLED) AT RONEZ, JERSEY (AFTER WELLS AND WOOLDRIDGE)

They would therefore regard granite as a product of replacement or *metasomatism*.

The magnitude of the processes involved makes it impossible to devise satisfactory control experiments under present laboratory conditions. The field evidence, showing only masses of frozen rock, can often be interpreted in several ways. The problem of the origin of batholithic bodies is one of the major unsolved problems of Geology.

MINERAL DEPOSITS

The geometrical form of many crystalline deposits of the metallic minerals is similar to that of bodies of igneous rock. Such deposits are, therefore, a special group of the igneous rocks, owing their characteristics to the low temperatures at which they consolidated. But during the formation of sedimentary rocks, materials of economic value may be concentrated to form bedded deposits. These include many of the ores of iron, the placer deposits yielding gold, silver,

diamond, etc., rock salt, gypsum, coal and the oil-bearing rocks, and they will be considered in the next chapter. We are concerned here only with mineral deposits, that have consolidated from the liquid or the gaseous state.

Mineral Veins or *Lodes* are one of their commonest forms of occurrence. The Cornish veins can be taken as typical. As Fig. X, 8, shows, a belt of mineralization extends through Cornwall in a north-easterly direction from just north of Land's End, past St. Austell to Tavistock. The individual lodes trend between east to west and north-east to south-west and cut both granite and country rock, proving that they were emplaced after the solidification of the granite. The veins fill fissures, whose walls are often slickensided, showing that the mineralizing solutions were 'fault guided', i.e. have risen along the planes of weakness formed by faults. The veins are composed of angular fragments of granite or country rock enclosed in *gangue* minerals (non-metallic minerals, usually of little economic value), through which are scattered stringers and pockets of the metallic ores. Sometimes cavities, known as 'vughs', are found, with well-formed crystals of either gangue or ore minerals growing towards the open space. The ore is mined by sinking shafts following the dip of the steeply inclined veins and driving levels along the strike with the hope of entering rich pockets of ore.

In many mines a regular zonation is found, the lode near the surface carrying zinc and copper ores, then copper alone, then a mixture of copper and tin ores and finally in the deepest parts of the mine only tin ores occur, whilst there are corresponding changes with depth in the nature of the gangue minerals. There is also a similar horizontal change along a level, if it extends far enough, the tin being found only in the granite, the other ores in the country rock. It is clear that there is a relation between the granite and the mineralization. Extremely fluid mineral-charged solutions must have emanated from the granite during the last stages of its consolidation and penetrated along faults and any other lines of weakness. The different mineral zones are due to the varying temperatures of formation of the various minerals. The tin ores crystallized first at temperatures of about 550°C., whilst the zinc ores, remaining fluid till the temperature had approached 400°C., were able to penetrate further.

Since their emplacement the copper ores, in particular, have suffered changes due to percolating rain water charged with carbon dioxide. The primary ore is a mixture of copper and iron sulphide, containing $34\frac{1}{2}$ per cent of copper. The copper sulphide is leached

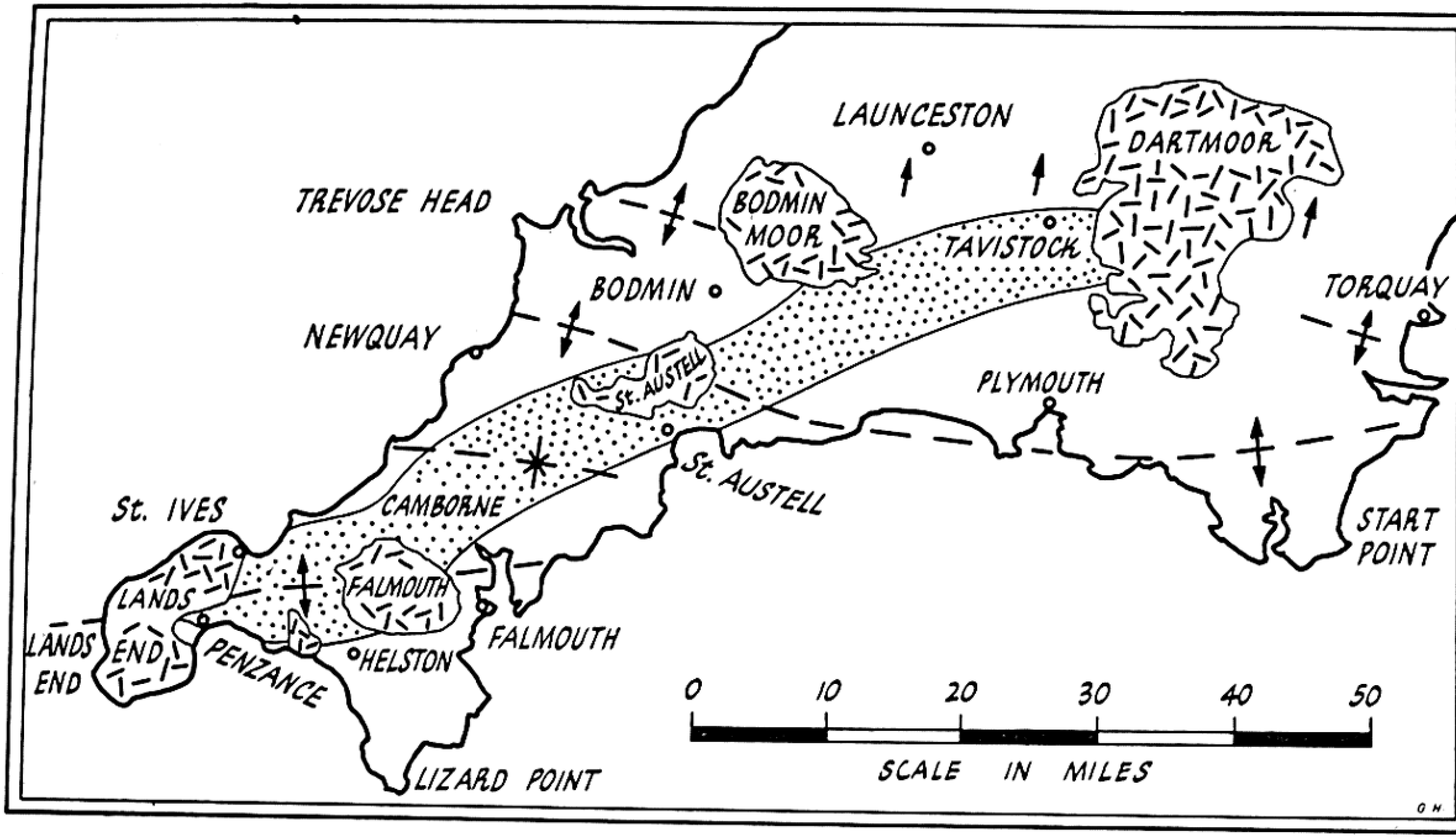


Fig. X, 8.—The Granite Bosses of South-West England and the Associated Belt of Mineralization (Stippled)

Arrows indicate dips in the country rocks and the broken lines axes of the main anticlines and synclines. The granites are clearly discordant to these structures.

out and is carried downwards to be precipitated in the *zone of secondary enrichment* as copper sulphide containing up to 70 per cent of copper whilst the leached upper portion, consisting mainly of iron oxides, forms the *gossan* or 'iron hat' of the miners. Below the zone of enrichment the ore reverts to its primary nature and may be too lean (uneconomic) to work.

The steeply inclined Cornish veins have clearly formed along fractures, in which mineral-charged *hydrothermal* solutions have crystallized. In regions of strongly folded rocks, mineral deposits often occur as irregular *reefs* along the axes of folds, where the stresses were less intense. An example is the gold-bearing saddle reefs of Bendigo in Australia. In a *stockwork* (Fig. X, 9) the rock is traversed by a multitude of irregular mineralized veinlets without any major veins.

Ores may also occur in more or less circular *pipes*, which are usually zoned in cross-section, with the payable ore restricted to certain sections. The famous diamond deposits of Kimberley in South Africa consist of pipes, probably in this case old explosion vents, filled with an unusual, and often brecciated, type of igneous rock in which crystalline diamonds occur. The 'blue ground' or the weathered rock is mined, broken down and then washed over tables coated with grease to which the diamonds stick, whilst the other minerals are washed away. On the average the yield of diamonds is about one fifteenth million part of the quantity of blue ground mined.

Obviously the concentration which it is economic to mine depends, in very large part, on the price paid for the product. In the case of a common metal like copper, an ore body containing one part of copper in twenty-five may be considered too 'lean', unless there are exceptional circumstances, such as ease of mining, ease of extraction or cheap transport which help to lower the price of the copper.

Pipes occur in Cornwall, but they are infilled not with mineral ores, but with kaolin. The pipes aligned along the same fissures as the tin and copper veins are due to carbonic acid vapours, rising from the granite at a late stage of its consolidation. These hot vapours have attacked the feldspars of the granite and have altered it to either China Clay or to China Stone, both of which are of great importance to the ceramic industry. This alteration of the feldspars must not be confused with that due to chemical weathering (p. 39). This is a *pneumatolytic* change, due to the attack of gases given off by the cooling granite.

But not all mineral deposits are of obvious hydrothermal or pneumatolytic origin. At Sudbury in Ontario occurs one of the

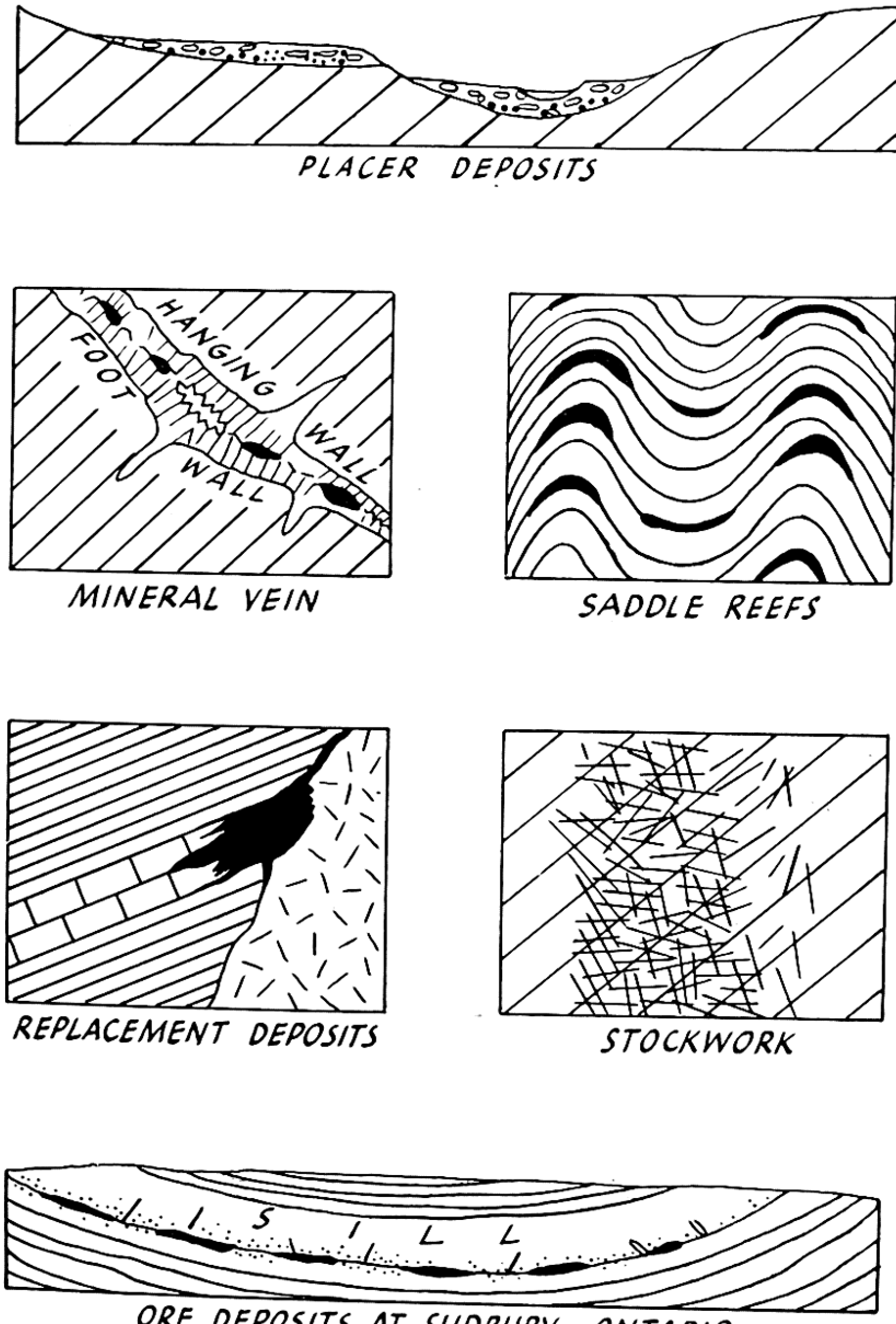


Fig. X, 9.—Types of Ore Deposits

Country rock is ruled, ores are in black. In the mineral vein, note the cavity or 'vugh' lined with well-formed crystals of gangue minerals. The replacement deposits have been formed along the contact of a granite intruded into shales (ruled) and limestone (bricks). Note that the offshoots are mainly in the limestone.

richest ore bodies in the World (Fig. X, 9), consisting of an enormous sill, 10,000 feet in thickness. The upper levels of the sill are barren of ore, but deeper down there are scattered grains of iron, copper and nickel, *disseminated* through the igneous rock. With increasing depth the minerals become aggregated into lenses or pockets, whilst along the irregular base of the sill are great bodies of solid ore of very high purity. These relations suggest that the heavy ores have been concentrated by gravity-differentiation during the consolidation of the sill, but there are many steeply inclined ore bodies as well, so another possibility is the injection of sulphide-rich magma, after the solidification of the igneous rock, along zones of weakness especially along the base of the sill.

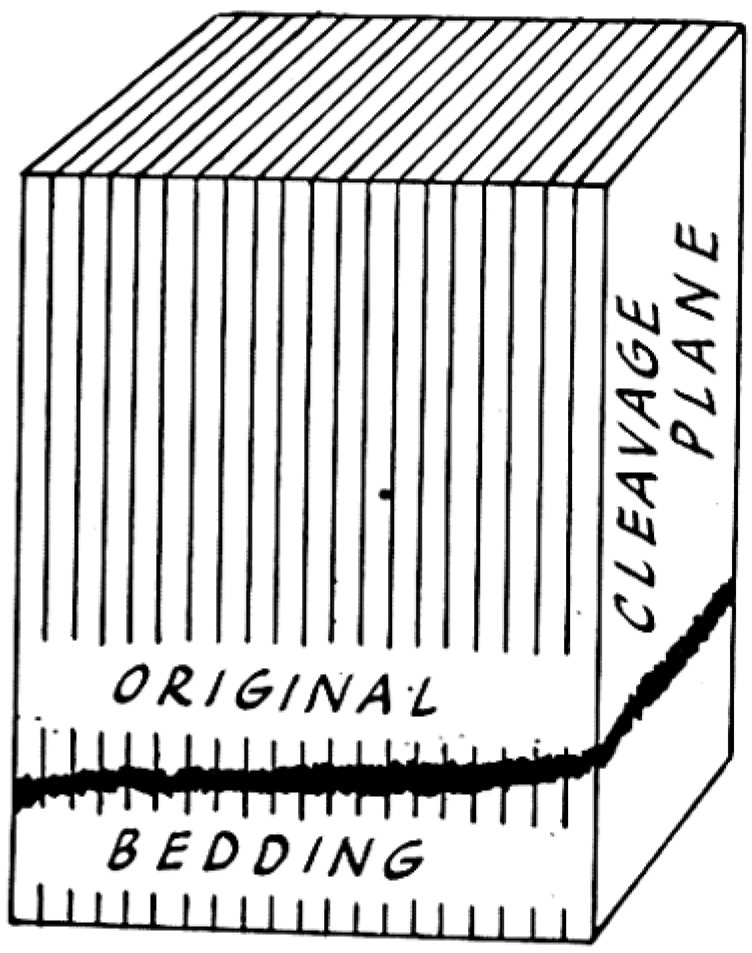
Ore bodies often occur in the contact zone of igneous with the country rock. To some extent they infill cavities, but more commonly the ores are *replacement deposits*, concentrated in certain types of country rock, especially limestones. Mineralizing solutions from the magma have attacked the limestone, which has passed into solution and the minerals have been deposited in its place. If the country rocks consist of alternations of shale and limestone, the shales will be almost barren, except very close to the contact, whilst rich ore bodies or *offshoots* may extend for hundreds of feet from the contact into the limestones.

METAMORPHIC ROCKS

Thermally metamorphosed rocks were produced by hot magma baking the rocks with which it came in contact. They are characterized by the presence of distinctive minerals which can only form at fairly high temperatures, and by signs of fusion. The width of the zone of altered rock is related to the nature and volume of the cooling magma. In the case of a dyke, a sill or at the base of a lava flow, the metamorphosed rock is usually a mere selvage, with its thickness measurable in inches; but granite batholiths are usually surrounded by a *metamorphic aureole*, a mile or more in width. The width of this aureole will partly reflect the shape of the igneous mass. A batholith with steeply plunging sides will produce a narrower aureole than one of the same volume, but with gently sloping sides. In a large metamorphic aureole, such as that of the Dartmoor Granite, it is possible to trace a gradual change from the country rock into baked and hardened material, spotted with minute crystals. Nearer the granite, these spots develop into crystals an inch or more

in length and it may be possible to show that the various metamorphic minerals are arranged in zones round the granite, corresponding to their different temperatures of formation. The contact with the granite will be sharp, with tongues of granite penetrating into the baked rocks of the aureole.

Dynamically metamorphosed rocks occur in those areas which have suffered great lateral compression. The pressure produces another suite of metamorphic minerals, those of high density and small volume, and also develops characteristic structures in the rocks. The rocks typically become foliated or schistose, recrystallization developing layers of parallel-lying minerals with complete oblitera-



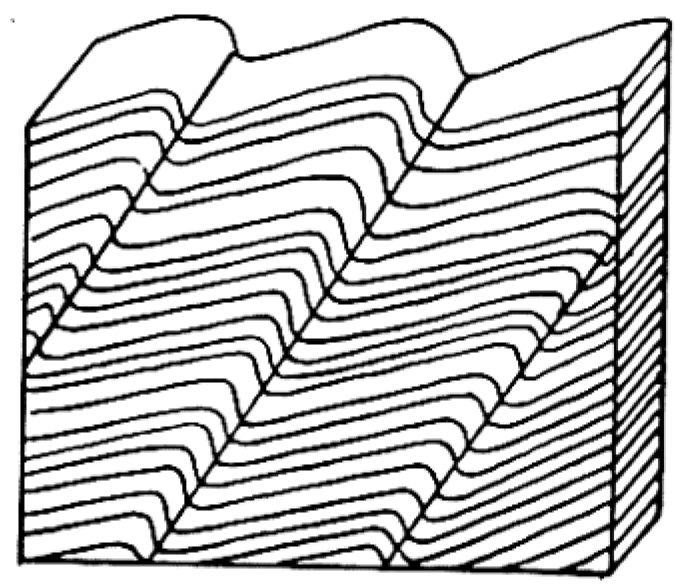


Fig. X, 10.—True Cleavage on Left and False or Strain-Slip Cleavage on Right

tion of pre-existing structures, such as bedding planes and fossils. The degree of schistosity reached depends partly on the magnitude of the pressure and partly on the nature of the rocks affected. Coarse-grained rocks, such as sands and pebble beds, will be welded together and made more compact, but will not become very schistose, though minor thrust planes may develop, along which masses of rock can move relative to one another. The finer-grained rocks, notably those of clay grade, will be converted to slates with new closely spaced planes of splitting or *cleavage* developed at a high angle to the original bedding. Less perfectly graded rocks, such as fine-grained volcanic ashes (pyroclasts), may develop not the true slaty cleavage, due to re-orientation of the minerals, but a *strain-slip cleavage*, produced by closely spaced planes of movement (Fig. X, 10).

In areas of *regionally* metamorphosed rocks, there is a combination of both thermal- and dynamo-metamorphism. During the intense folding movements, the rocks were forced down into regions of high temperature and became thermally metamorphosed and also were affected by intrusion of molten material, either in the form of batholiths, or by *lit-par-lit* penetration along the planes of weakness. But at the same time the great pressures were liable to produce the minerals and structures typical of dynamo-metamorphism. In regions of intensely regionally metamorphosed rocks, it is often extremely difficult to work out the sequence of metamorphic changes, and still more to be sure whether the greatly altered rocks were originally of sedimentary or of igneous origin.

CHAPTER XI

Identification of Minerals

A MINERAL is a substance of inorganic origin, having a definite chemical composition and definite physical properties. Minerals occur either as crystals of regular shape, bounded by plane surfaces, or as irregularly shaped masses. In either case the molecules, which build up the minerals, are regularly arranged, but in the massive types this regular arrangement is not reflected in their surface form, though it does determine many of their physical properties such as the ease of splitting or cleavage.

One feature that distinguishes minerals from organic substances is that minerals grow by the addition of material to their surfaces, whilst organic substances (plants and animals) lay down fresh material internally. One can often find specimens of one mineral on the surface of which are crystals of another mineral, showing that a change occurred in the chemical composition of the liquid from which crystallization was taking place.

A mineral can usually only assume its characteristic crystal form if it has adequate space in which to grow. The best crystals are to be found lining the walls of cavities in rocks. A distinction is drawn between minerals that are *crystallized* with definite crystals, those that are *crystalline* being composed of a confused mass of irregularly formed crystals, and those which are *cryptocrystalline*. The crystalline nature of the latter is not apparent in their appearance.

Minerals are identified by their crystal form (if developed) and by their physical properties. In the case of cryptocrystalline minerals and of massive minerals we have to rely entirely on physical properties for identification under field conditions. Special techniques, including the examination of their molecular structure by X-rays, have been devised for the identification of minerals, especially the rarer ones and those of which only a very small quantity is available.

The Physical Properties of Minerals

Colour. A limited number of minerals are of a distinctive colour but this may be altered by the presence of small quantities of impurities. Certain minerals show a range of colours, e.g. quartz and fluor-spar. Minerals of distinctive shades of colour often have special names, e.g. rose quartz and Blue John, the purple variety of fluor-spar. To identify a mineral by colour alone, without considering its other physical properties, is unwise.

The Lustre of a mineral, depending on the amount of light reflected from its surface, is sometimes distinctive. The terms used, adamantine (like a diamond), dull, greasy, metallic, pearly, resinous, silky, vitreous (like glass), are self explanatory. If objects are reflected by the surface of the mineral, the adjective splendent is often added, e.g. marcasite has a splendent metallic lustre and is often used in jewelry. The lustre of a mineral may differ according to whether it is crystallized or massive as in zinc blende or, as in gypsum, it may vary between cleavage and crystal faces.

Certain minerals show a play of colours on the surface and if this is associated with a milky appearance, as in opal, it is called *opalescence*, but if the lustre is more brilliant, as in stibnite, it is called *iridescence*. Others, e.g. copper pyrites, are apt to tarnish rather easily on the surface and may become iridescent (peacock copper), but the true colour can be revealed by scraping off the surface layers.

The Streak of a mineral, the colour shown by its powder, may be the same or may be different from that of the hand specimen; the oxides of iron, in particular, can be easily identified by their distinctive streaks. To determine streak, scrape a small quantity off the mineral with a knife (do *not* disfigure a crystal face in doing this) and crush the powder either on white paper or better still on a porcelain streak plate.

The Weight of a mineral is normally only diagnostic in the case of exceptionally heavy minerals. The specific gravity (S.G.) of a mineral is the ratio of its weight to that of the same volume of water. Barytes can be distinguished from other whitish minerals by its greater S.G. (4·5) as compared with the usual values of 2·5 to 3, whilst cinnabar, cassiterite, native copper and native gold have still higher specific gravities (*see* Tables VI and VII). With a little practice the heavier minerals can be recognized in the hand, but for more refined tests, the mineral is placed in a series of liquids of increasing S.G., until it just floats.

Hardness. In 1820 Moh arranged certain common minerals in

the following scale of hardness, the lower values being scratched by the higher:

1. Talc	6. Orthoclase Feldspar
2. Gypsum	7. Quartz
3. Calcite	8. Topaz
4. Fluor-spar	9. Corundum
5. Apatite	10. Diamond

This is entirely an arbitrary scale, the differences in real hardness between the selected minerals being most irregular, but it is a very convenient scale to use. The hardness of a finger-nail is about 2·5, of a knife about 6·5, so that quartz cannot be scratched by either a finger-nail or by steel, but calcite can be scratched with a knife, a quick test for distinguishing between two common minerals with many rather similar properties.

Form. Certain massive minerals assume, if possible, a definite form or habit. The names applied to some of these forms, such as columnar or fibrous, are self explanatory, the other common terms are defined below:

amorphous ...	... non-crystalline and therefore without a distinctive shape, e.g. opal.
arborescent ...	... tree-like branching, e.g. copper.
botryoidal ...	... like a bunch of grapes, e.g. chalcedony.
foliated ...	... thin leaves, e.g. talc.
laminae ...	... thin plates, e.g. graphite.
mammillated	... large curved surfaces, e.g. limonite.
reniform ...	... strongly curved surfaces like kidneys, e.g. haematite.

Fracture. The nature of the surface along which a mineral breaks is sometimes characteristic.

The chief types of fracture are:

conchoidal ...	... curved surface, often with concentric waves, gradually diminishing from the place of the blow; shown by quartz.
uneven ...	... as in copper pyrites, as distinct from even, as in galena.
hackly ...	... surface covered by sharp jagged protruberances, as in cast iron.

Cleavage, on the other hand, is the tendency for minerals to split along definite planes, which are related to the crystal structure. The micas, for example, have an extremely well developed single cleavage

and split easily into thin sheets, whilst rock salt breaks into cubes. These are examples of minerals with perfect cleavage, but other minerals have only a poorly developed cleavage and are just as likely to fracture irregularly as cleave, whilst amorphous minerals have no definite direction of cleavage.

Taste, Smell, Feel, etc. These are properties that are diagnostic in only a few cases. Cubes of rock salt can be identified from cubes of white fluor-spar by their brinish taste, whilst a few minerals emit a characteristic smell when struck with steel and others, such as talc, feel greasy.

Magnetism. Magnetite is the only common mineral affected by an ordinary magnet, but a considerable number of minerals are attracted by an electro-magnet. This property is of considerable value in the metallurgical treatment of minerals in separating the ore from the gangue minerals. Many minerals have to be roasted to make them sufficiently magnetic for electro-magnetic separation. In this way iron pyrites can be separated from zinc blende, magnetite from apatite, etc.

Another widely used method of concentration is the 'flotation process' and this has permitted the economic working of many low-grade ore deposits. This process depends on the fact that certain sulphidic minerals such as zinc blende can be 'oiled'. The finely crushed ore is mixed with water then a small quantity of a suitable oil is added and a froth is produced by blowing air into the liquid. The oiled particles of the metallic sulphides adhere very strongly to the bubbles, whilst the gangue minerals are not attracted. The bubbles can be skimmed off and the sulphides concentrated from them.

Crystallography or the Study of Crystals

Crystals are bounded by plane faces meeting along edges. The faces and edges of a crystal are arranged in a regular manner, constituting the symmetry of the crystal. There are three elements of symmetry; the centre, the planes and the axes.

A crystal has a *centre of symmetry*, if each face is balanced by a similar face (parallel to it and of the same form) on the diametrically opposite side of the crystal.

A *plane of symmetry* divides a crystal into two parts, which are mirror images of each other.

An *axis of symmetry* is an imaginary line about which a crystal can be rotated, so that corresponding faces come into the same position. According to the number of times this occurs during one complete

revolution, the axis is said to be of twofold, threefold, fourfold or sixfold symmetry (Fig. XI, 1).

By combining the presence or absence of a centre of symmetry with varying numbers of planes of symmetry and axes of different fold symmetry, 32 different *Classes* of symmetry can be recognized. The commoner minerals, however, crystallize in only 11 of these

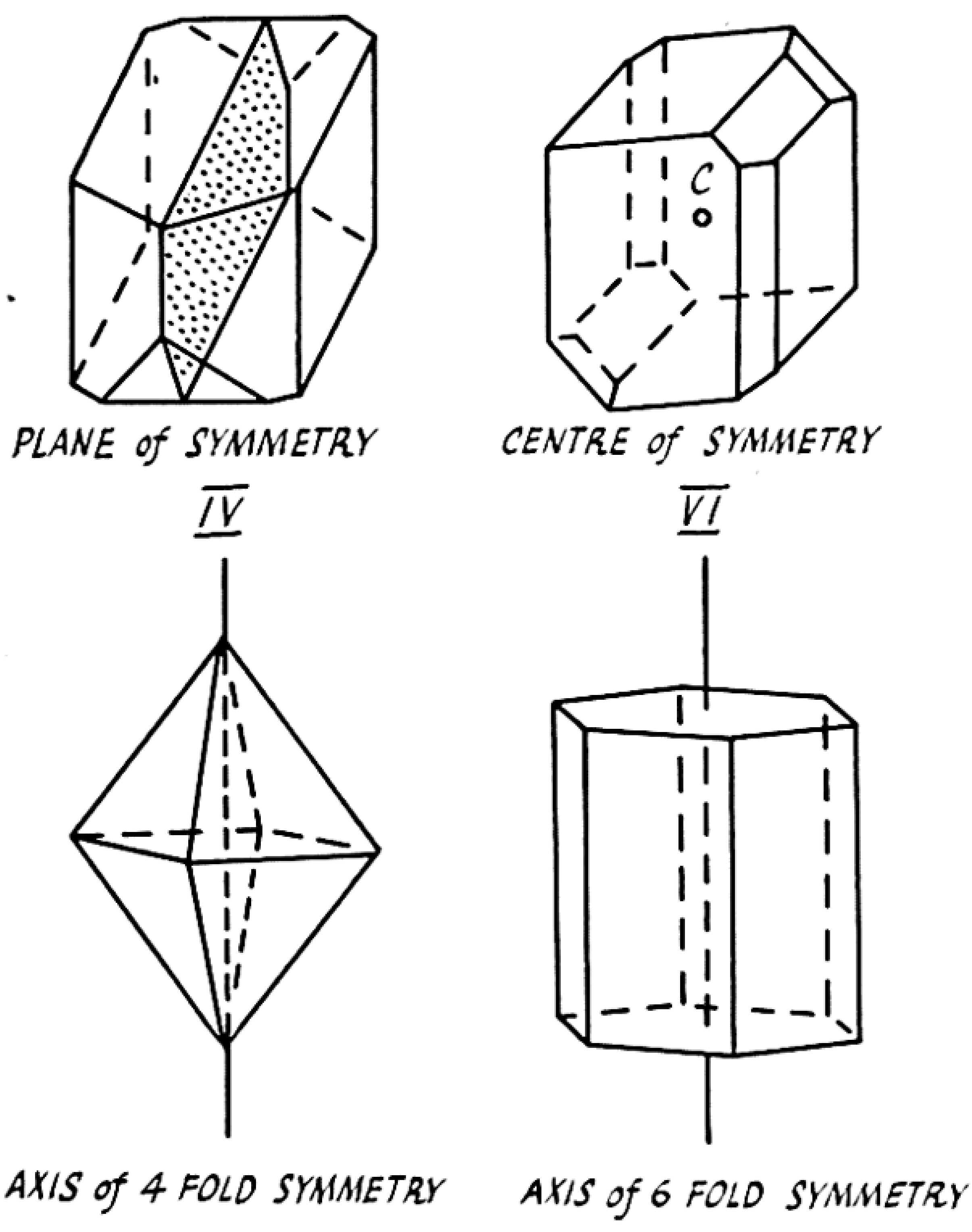


Fig. XI, 1.—The Elements of Symmetry

classes. Rare minerals or laboratory-made compounds provide examples of most of the remaining classes, but two of the classes are mathematical abstractions, for no minerals or synthetic compounds crystallizing in them have, as yet, been found.

Crystallographic Axes

In solid geometry the position of a plane in space is determined by the intercepts made by the plane on a number of lines or axes meeting at a point or origin. The position of the face of a crystal is

similarly determined in relation to the crystallographic axes, which are either three or four in number. One of the axes is always vertical, and if four are present the other three are all horizontal, whilst if there are three axes, the remaining two are either horizontal or inclined to the vertical axis.

The crystallographic axes are regarded as having direction only, for as they can be extended to infinity, they cannot have a definite

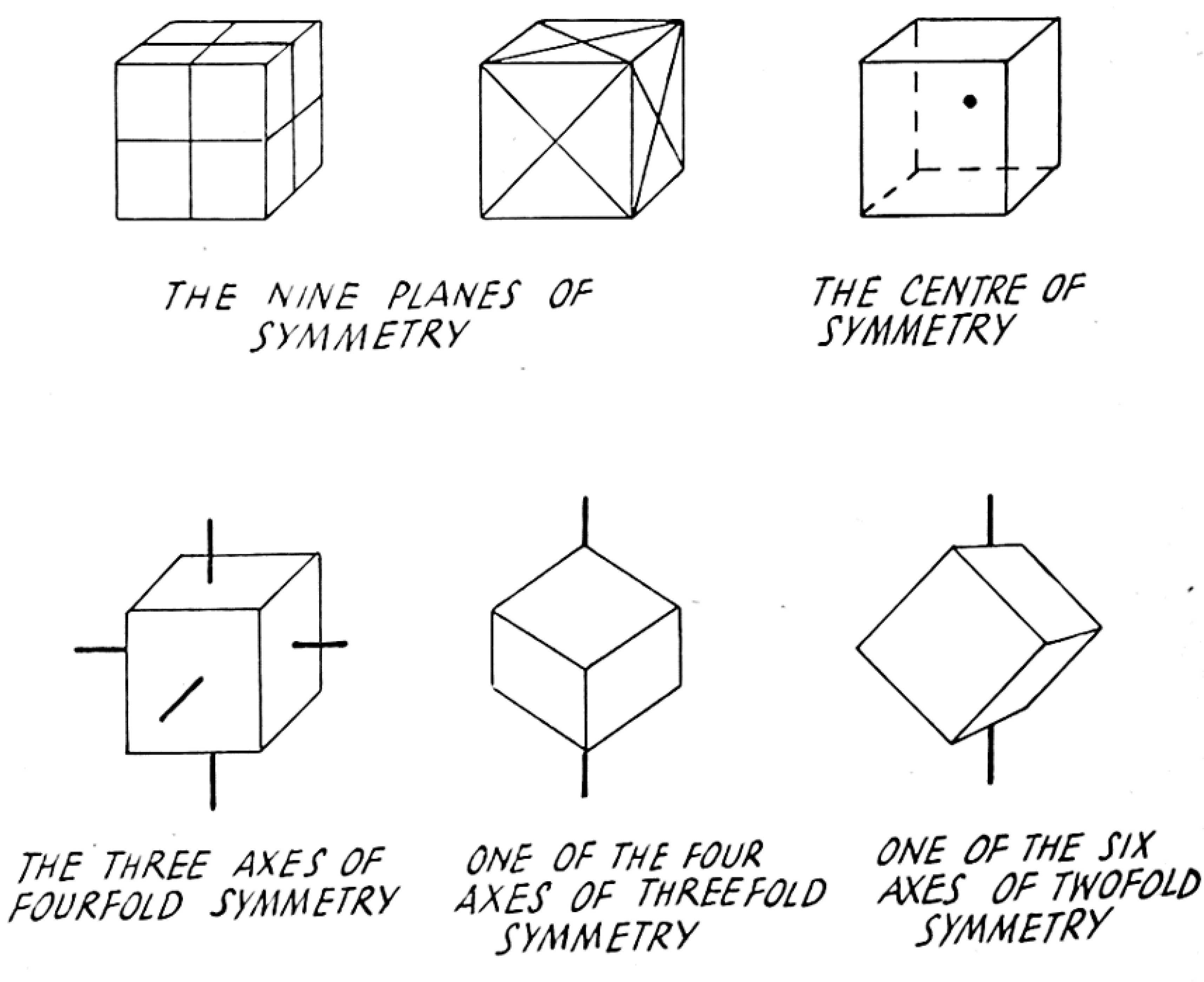


Fig. XI, 2.—Symmetry Elements of a Cube

length. On examining a crystal we usually find that it is composed of a number of faces, some of which may be parallel to one or more of the axes, whilst others (produced if necessary) cut all the axes. If we select two faces, inclined at differing amounts to all the axes, the intercepts made by the two faces on each axis will be different. But if we take one of the faces as the unit face and regard its intercepts as units of measurement or *parameters*, then we find that the intercepts made by the face of different inclination can be expressed in simple terms of the parameters, i.e. half, equal to, twice that of the

unit face, etc. It must be realized that the unit face chosen need not intercept all axes at the same distance from the origin, and hence that the parameters need not be the same on all axes.

The Crystal Systems

Each of the 32 classes of symmetry can be placed in one or other of the 7 Crystal Systems, which are defined in terms of the relation and number of their crystallographic axes and the relations of the parameters along these axes (*see* Table I, pages 138, 139).

By some authorities the Trigonal System is not separated from the Hexagonal System, the axes being the same, but the vertical crystallographic axis of the Hexagonal System is an axis of sixfold symmetry, whilst in Trigonal crystals the same axis is only of threefold symmetry.

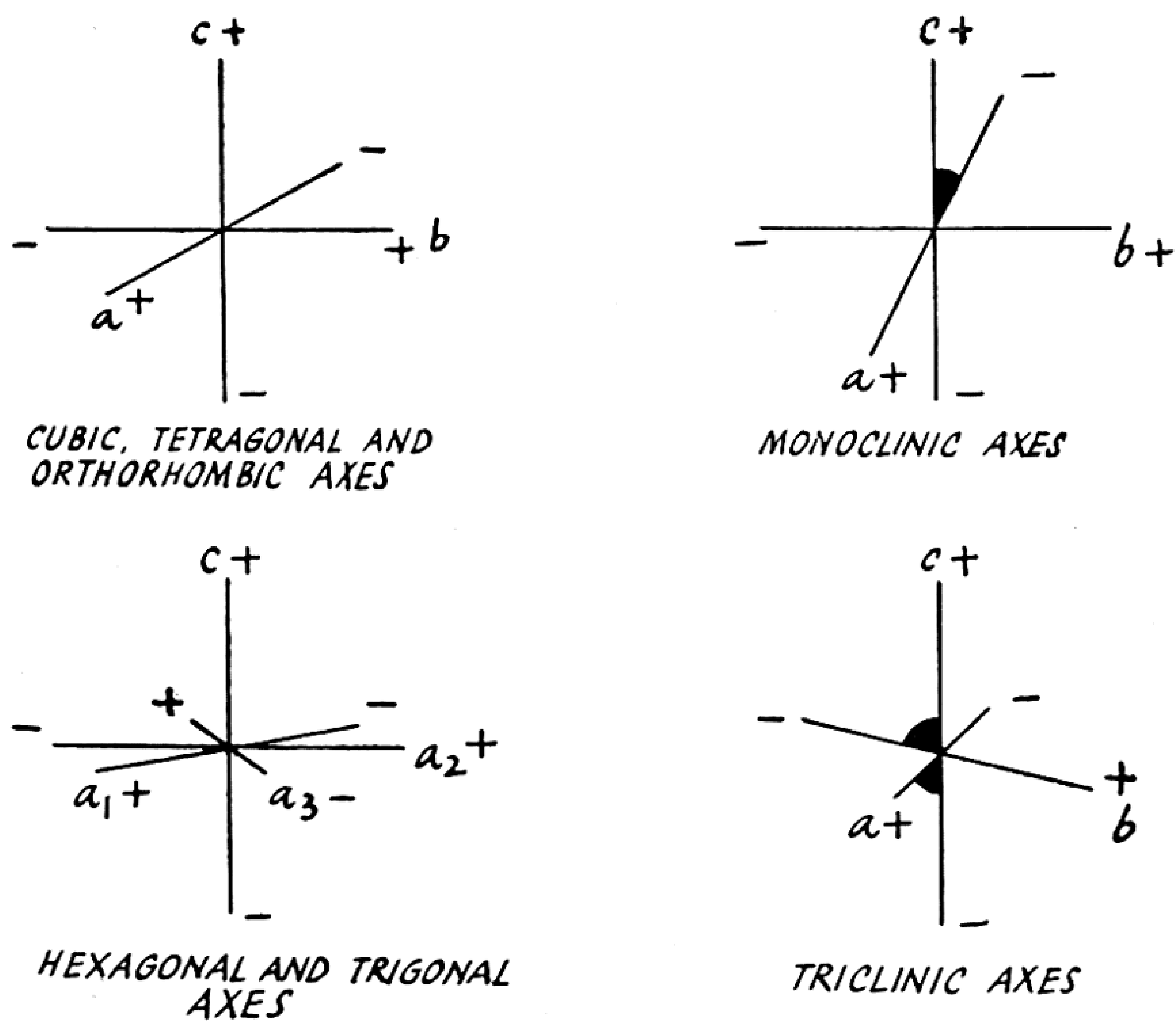


Fig. XI, 3.—Axes of the Different Crystal Systems

N.B.—All interaxial angles are right angles except those shaded black.

So far we have given the angles between the different axes, but apart from one axis being vertical, we have not fixed the position of the remaining axes relative to the person who is studying a crystal. For systems other than the Hexagonal and the Trigonal, one of the two non-vertical axes, the *a* axis, is regarded as pointing straight at the observer, whilst the other, the *b* axis, extends from right to left. The vertical axis is called the *c* axis. For Monoclinic crystals, the *b* axis is horizontal and the *a* axis slopes downwards and towards the observer. In the Hexagonal and Trigonal Systems, the *c* axis is vertical, and there is no *b* axis, the three horizontal axes being all *a* axes numbered as shown in Fig. XI, 3. As shown, one end of each axis is regarded as positive and the other as negative.

Crystal Notation

Crystallography is an exact science and it is therefore essential that the crystal to be studied is oriented correctly, that is, held so that all its faces can be related to the system of the highest possible symmetry. A crystal should not be regarded as Orthorhombric, if it can be so held that it fits the Tetragonal axes and so on.

The next step is to annotate the crystal, that is, to state the position of each face relative to the crystallographic axes. We have already seen that the position of a face in relation to the origin can be given in terms of the intercepts made along the axes *a*, *b*, *c* or a_1, a_2, a_3, *c* according to the system. But in the system of notation devised by Miller, the indices of a face are obtained by dividing the parameters of each axis by the intercepts, i.e. suppose that the intercepts of a face are *a*, 2*b*, *c*, then its Millerian indices are $\frac{a}{a}, \frac{b}{2b}, \frac{c}{c}$ or 1, $\frac{1}{2}$, 1. To avoid fractions this is written 212. If a face is parallel to an axis, then its intercept is infinity and its index on that axis is zero, for any quantity divided by infinity is zero. Therefore a face with intercepts 2*a*, ∞*b*, *c* will have indices $\frac{a}{2a}, \frac{b}{\infty b}, \frac{c}{c}$ or 102. The indices of a face are usually enclosed in round brackets, e.g. (102), whilst a bar over the figure means that the face cuts that axis on its negative side.

If we place a face cutting the *a* axis of the Cubic System at unit parameter and parallel to the other two axes, that is, a face with indices (100), then to satisfy the symmetry requirements of the system there must be 5 other faces with the same relation to the axes and with

indices ($\bar{1}00$), (010), ($0\bar{1}0$), (001), and ($00\bar{1}$) (Fig. XI, 4). These faces, which are all similar faces as regards their symmetry, make up a *form*. Forms may be either closed, enclosing a space, as in a cube, or they may be open forms, which can only enclose a space if they are combined with one or more other forms. Every crystal is made up of one or more forms and can be described most simply in terms of the forms present. A form is indicated by enclosing the index of one face in braces, e.g. {111}, and this indicates that all the other faces of the form are present. The number of faces present in different forms varies from one to forty-eight.

Seven forms are usually recognized in each crystal class. Below are summarized the forms of the simplest classes, together with the indices of each form and the number of faces that comprise it. If the index is given in terms of h, k, i or l, this means that the inclination

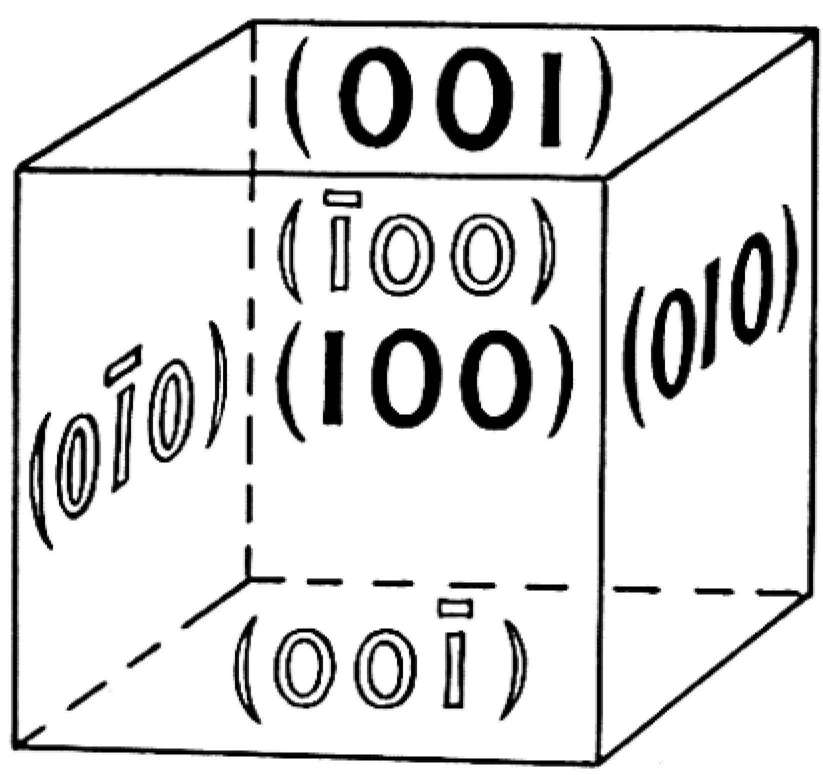


Fig. XI, 4.—Millerian Indices of Each Face of a Cube

Those on the faces hidden in a front view are shown in double lines.

of the face to the axes may vary. A double-ended pyramid with 12 similar faces at either end will still be a dihexagonal bipyramid, whether it is squat or very tapering, but the intercepts of the faces and therefore their indices will be different in the two cases. On the other hand, the faces of a cube intersect the axes at unit parameter and its index is therefore {100}.

TABLE I

THE COMMONER CLASSES OF THE CRYSTAL SYSTEMS

System	Number and arrangement of crystallographic axes	Relation of Parameters	Classes	Elements of Symmetry					
				Centre	Planes	Axes			
						(ii)	(iii)	(iv)	(vi)
Cubic or Isometric	3 axes, all at right angles	Equal on the three axes	Galena	Present	9 (3a, 6d)	6	4	3	—
			Tetrahedrite	Absent	6 (6d)	3	4	—	—
			Pyrite	Present	3 (3a)	3	4	—	—
Tetragonal	3 axes, all at right angles	Equal on the two horizontal axes, different for the vertical axes	Zircon	Present	5 (3a, 2d)	4	—	1	—
Hexagonal	1 vertical and 3 horizontal axes, at angles of 120° to each other	Equal on the 3 horizontal axes, different for the vertical axis	Beryl	Present	7 (4a, 3d)	6	—	—	1
Trigonal	Similar	Similar	Calcite	Present	3 (3d)	3	1	—	—
			Tourmaline	Absent	3 (3d)	—	1	—	—
			Quartz	Absent	—	3	1	—	—
Orthorhombic	3 axes, all at right angles	Differing on each axis	Olivine	Present	3 (3a)	3	—	—	—

Monoclinic	1 vertical and 1 horizontal axis, with the 3rd axis inclined to the vertical axes, but at right angles to the horizontal axis	Differing on each axis	Augite	Present	1 (1a)	1	—	—	—
Triclinic	A vertical axes with two other axes inclined to it, but at right angles to each other	Differing on each axis	Albite	Present	—	—	—	—	—
				Axial planes of symmetry are indicated by a; diagonal one by d.					

TABLE II

THE FORMS OF THE COMMONER CLASSES OF THE CRYSTAL SYSTEMS

Cubic or Isometric System (Fig. XI, 5)

Galena Class

1. cube	{100}	closed form of	6 faces
2. octahedron	{111}	,, ,, ,,	8 ,,
3. rhombic dodecahedron	{110}	,, ,, ,,	12 ,,
4. tetrakishexahedron	{hko}	,, ,, ,,	24 ,,
5. triakisoctahedron	{hhl}	,, ,, ,,	24 ,,
6. icositetrahedron	{hll}	,, ,, ,,	24 ,,
7. hexakisoctahedron	{hkl}	,, ,, ,,	48 ,,

Pyrite Class

1. cube			
2. rhombic dodecahedron			
3. octahedron			
4. triakisoctahedron			
5. icositetrahedron			
6. pentagonal dodecahedron ...	{210}	closed form of	12 faces
7. diploid	{321}	,, ,, ,,	24 ,,

The characteristic form of the *Tetrahedrite Class* is the four-faced tetrahedron {111}.

Tetragonal System (Fig. XI, 6)

Zircon Class

1. basal pinacoid	{001}	open form of	2 faces
2. prism of the first order	{110}	,, ,, ,,	4 ,,
3. prism of the second order	{100}	,, ,, ,,	4 ,,
4. ditetragonal prism	{hko}	,, ,, ,,	8 ,,
5. bipyramid of the first order	{hhl}	closed ,, ,,	8 ,,
6. bipyramid of the second order ...	{hol}	,, ,, ,,	8 ,,
7. ditetragonal bipyramid	{hkl}	,, ,, ,,	16 ,,

Hexagonal System (Fig. XI, 6)

Beryl or Holosymmetric Class

1. basal pinacoid	{0001}	open form of	2 faces
2. prism of the first order	$\{10\bar{1}0\}$	,, ,, ,,	6 ,,
3. prism of the second order	$\{11\bar{2}0\}$	,, ,, ,,	6 ,,
4. dihexagonal prism	$\{hi\bar{k}o\}$	,, ,, ,,	12 ,,
5. bipyramid of the first order ...	$\{ho\bar{h}l\}$	closed ,, ,,	12 ,,
6. bipyramid of the second order ...	$\{hh\bar{2h}l\}$	,, ,, ,,	12 ,,
7. dihexagonal bipyramid	$\{hi\bar{k}l\}$	,, ,, ,,	24 ,,

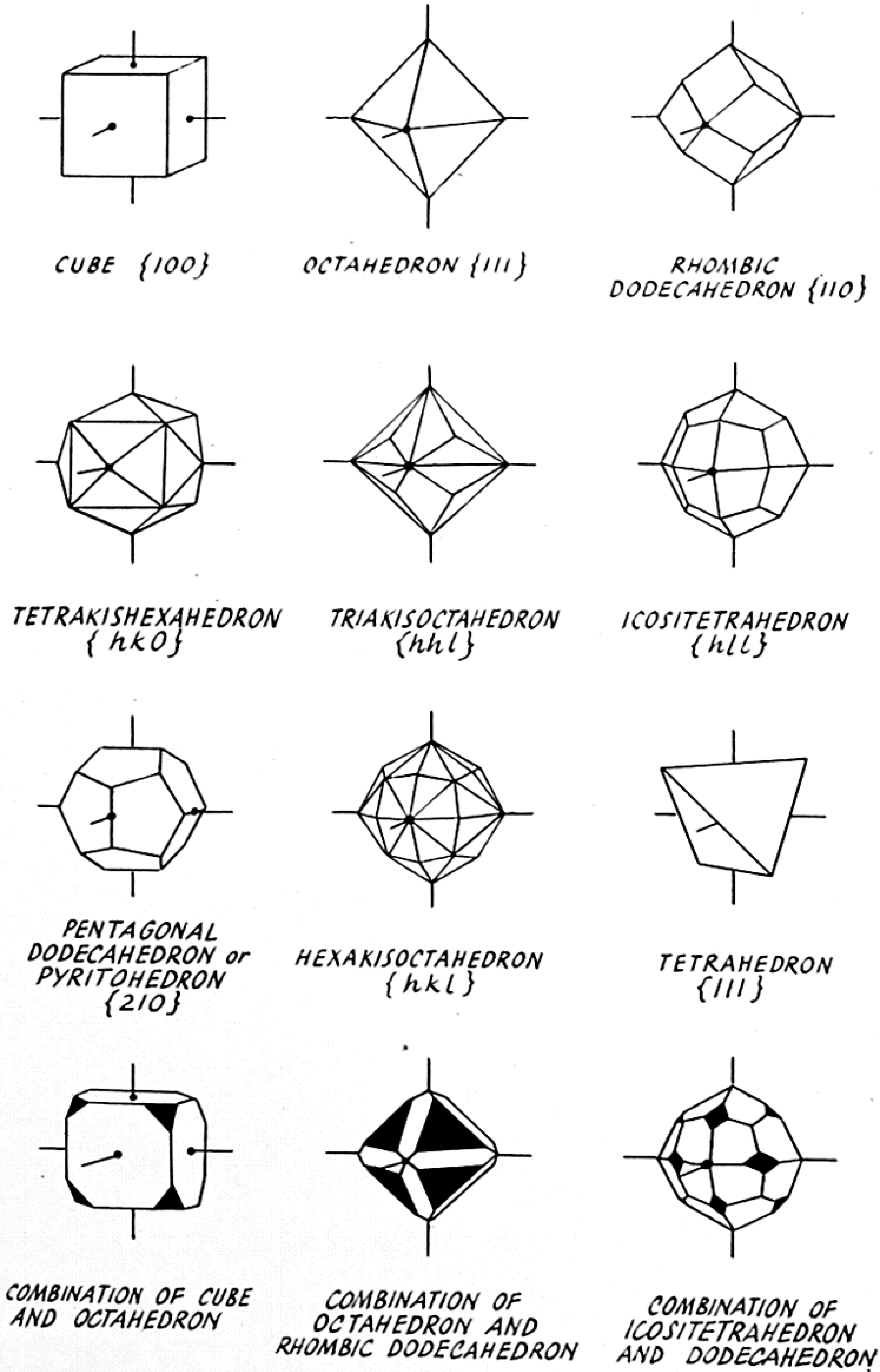


Fig. XI, 5.—FORMS OF THE CUBIC SYSTEM

Trigonal System (Fig. XI, 6)

Calcite or Holosymmetric Class

1.	basal pinacoid		
2.	first order hexagonal prism		
3.	second order hexagonal prism		
4.	dihexagonal prism		
5.	second order hexagonal bipyramid		
6.	rhombohedron	$\{h0\bar{h}l\}$	closed form of 6 faces
7.	scalenohedron	$\{hi\bar{k}l\}$	,, ,, ,, 12 ,,

Tourmaline Class

1.	basal plane	$\{0001\}$	1 face only
2.	second order hexagonal prism ...	$\{11\bar{2}0\}$	open form of 6 faces
3.	trigonal prism	$\{10\bar{1}0\}$	,, ,, ,, 3 ,,
4.	ditrigonal prism	$\{hi\bar{k}0\}$	,, ,, ,, 6 ,,
5.	trigonal pyramid	$\{h0\bar{h}l\}$	,, ,, ,, 3 ,,
6.	second order hexagonal pyramid ...	$\{hh\overline{2h}l\}$	,, ,, ,, 6 ,,
7.	ditrigonal pyramid	$\{hi\bar{k}l\}$	,, ,, ,, 6 ,,

As there is no centre of symmetry nor horizontal axes of symmetry, the upper and lower ends of crystals of the Tourmaline Class do not balance. The pyramids are hemimorphic, i.e. composed of only the upper or lower faces of the bipyramids of the classes of higher symmetry.

Quartz Class

1.	basal pinacoid	$\{0001\}$	open form of 2 faces
2.	first order hexagonal prism	$\{10\bar{1}0\}$	,, ,, ,, 6 ,,
3.	second order trigonal prism	$\{2\bar{1}\bar{1}0\}$	,, ,, ,, 3 ,,
4.	ditrigonal prism	$\{hi\bar{k}0\}$	,, ,, ,, 6 ,,
5.	rhombohedron	$\{h0\bar{h}l\}$	closed ,, ,, 6 ,,
6.	trigonal bipyramid	$\{hh\overline{2h}l\}$	,, ,, ,, 6 ,,
7.	trigonal trapezohedron	$\{hi\bar{k}l\}$	,, ,, ,, 6 ,,

Orthorhombic System (Fig. XI, 7)

Olivine Class

1.	basal pinacoid	$\{001\}$	open form of 2 faces
2.	front pinacoid	$\{100\}$	,, ,, ,, 2 ,,
3.	side pinacoid	$\{010\}$	,, ,, ,, 2 ,,
4.	first order prism	$\{011\}$	,, ,, ,, 4 ,,
5.	second order prism	$\{101\}$	,, ,, ,, 4 ,,
6.	third order prism	$\{110\}$	,, ,, ,, 4 ,,
7.	bipyramid	$\{111\}$	closed ,, ,, 8 ,,

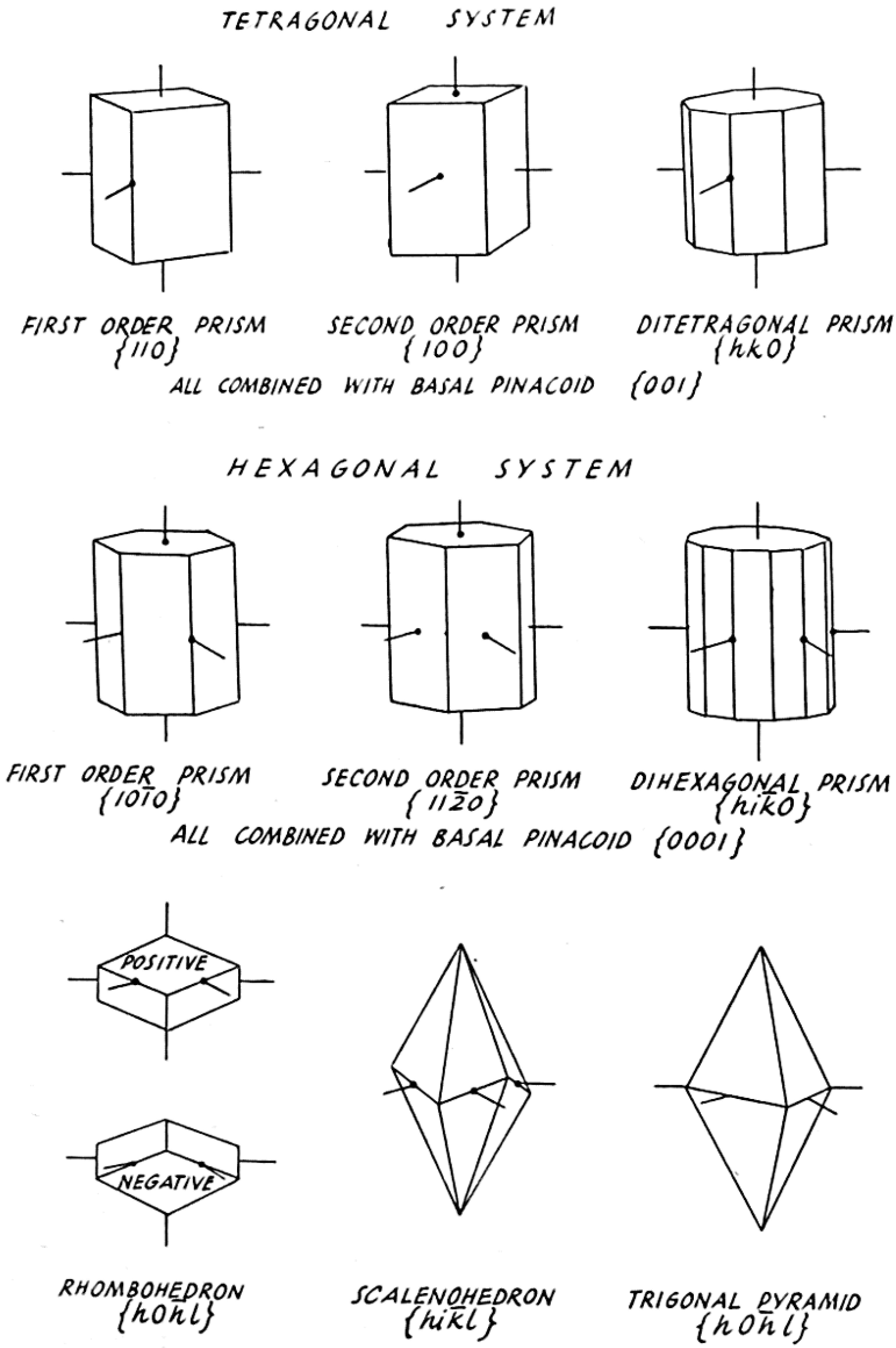


Fig. XI, 6.—Some Forms of the Tetragonal, Hexagonal and Trigonal Systems

Monoclinic System (Fig. XI, 7)

Augite Class

1. basal pinacoid	{001}	open form of 2 faces
2. front pinacoid	{100}	,, ,, ,, 2 ,,
3. side pinacoid	{010}	,, ,, ,, 2 ,,
4. first order prism	{011}	,, ,, ,, 4 ,,
5. third order prism	{110}	,, ,, ,, 4 ,,
6. hemiprism	{hol}	,, ,, ,, 2 ,,
7. hemibipyramid	{hkl}	,, ,, ,, 4 ,,

The hemiprism and hemibipyramid are due to the slope of the *a* axis.

The Recognition of Forms Present

The study of crystals has shown that they always obey the following laws:

(i) Law of Constancy of Symmetry. All crystals of a particular mineral have the same symmetry.

(ii) Law of Constancy of Interfacial Angles. All crystals of a particular mineral have the same angle between corresponding faces.

Crystals are often not perfect examples of the forms present. Owing to the conditions of crystallization, it may well happen that certain faces of a particular form are able to develop much better than the other faces and the result will be a *malformed* or *distorted* crystal, which may at first sight appear distinctly puzzling (Fig. XI, 8). But if the angles between the like faces are measured, they will all be the same and will also be the same as those of a perfect example of that particular mineral. Examination of interfacial angles is, therefore, of the greatest value in the recognition of the forms present.

The interfacial angles are measured by a *goniometer*, consisting in its simplest form of a graduated protractor with an arm rotatable about the index point. When using such a contact goniometer, place it normal to the edge to be measured, with one face of the crystal along the base of the goniometer and the arm touching the other face. The interfacial angle is then read off from the scale, whilst the supplement of this angle gives the angle between the normals to the two faces. More advanced types of goniometers are elaborate optical instruments, designed for precise measurement of very small crystals.

To analyse a crystal that is a combination of several forms it is often necessary to make a plan of it. A drawing is usually not completely satisfactory, for apart from the skill required, the technique

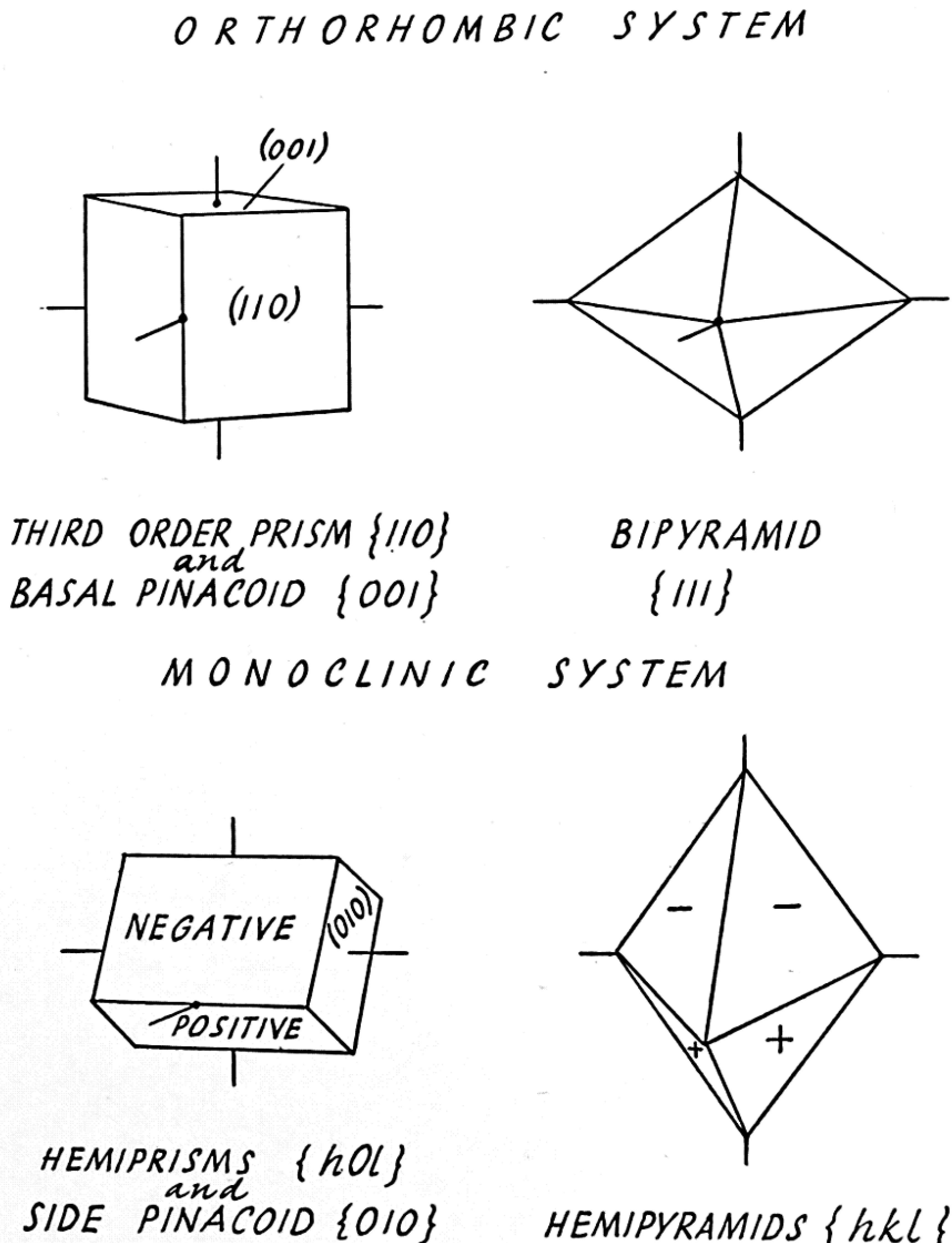


Fig. XI, 7.—Some Forms of the Orthorhombic and Monoclinic Systems

used for a perspective drawing means that those edges and planes of the crystal, which are parallel, appear to converge towards the 'vanishing point'. An improvement is to imagine the vanishing point removed to infinity, so that these edges can be drawn parallel. It is much better, especially for complex crystals, to use some form of entirely geometrical projection. Space does not permit adequate treatment of such projections, especially of the stereographic projection, which can be used not only for analysing crystals, but as a method for the teaching of Crystallography.

Combinations of Crystals

So far we have considered isolated crystals. Crystals, however, often occur as combinations, either as *Parallel Growths* or *Irregular Aggregates* or as *Twinned Crystals* (Fig. XI, 9). Twins consist of two

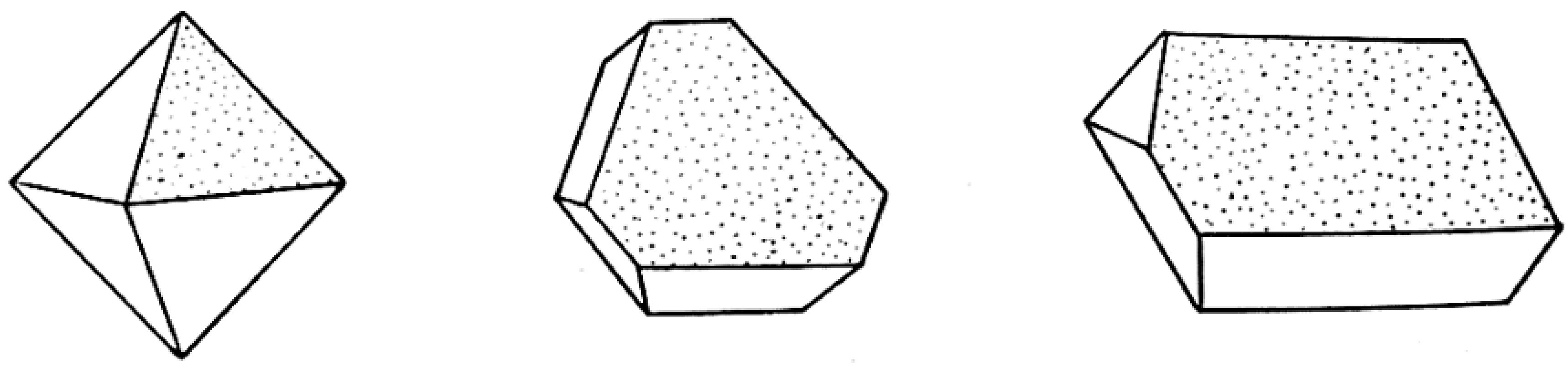


Fig. XI, 8.—Malformed Crystals
Perfect Octahedron on left, distorted ones on right. The corresponding face is shaded and the interfacial angles are the same in each crystal.

or more crystals of the same mineral having a different orientation, but symmetrically related to each other. The presence of re-entrant angles is very characteristic of twinned crystals.

There are many different types of twinning; simple twins may be either contact twins, with the two halves joined along a composition plane, or interpenetrant twins. The relation of the two parts of the twin can often be explained by imagining that the one part of the crystal has been rotated through 180° relative to the other. This, of course, has not actually happened for the twin has grown just like any other crystal. The axis on which rotation might have taken place is called the *twin axis*, and the plane perpendicular to it the *twin plane*, which often coincides with the *composition plane*. In another type of twin, the *reflection twin*, the two parts are mirror images of each other reflected across the twin plane.

Twins may be much more complex than this. Compound twins are often of one of two types. They may be more or less circular in

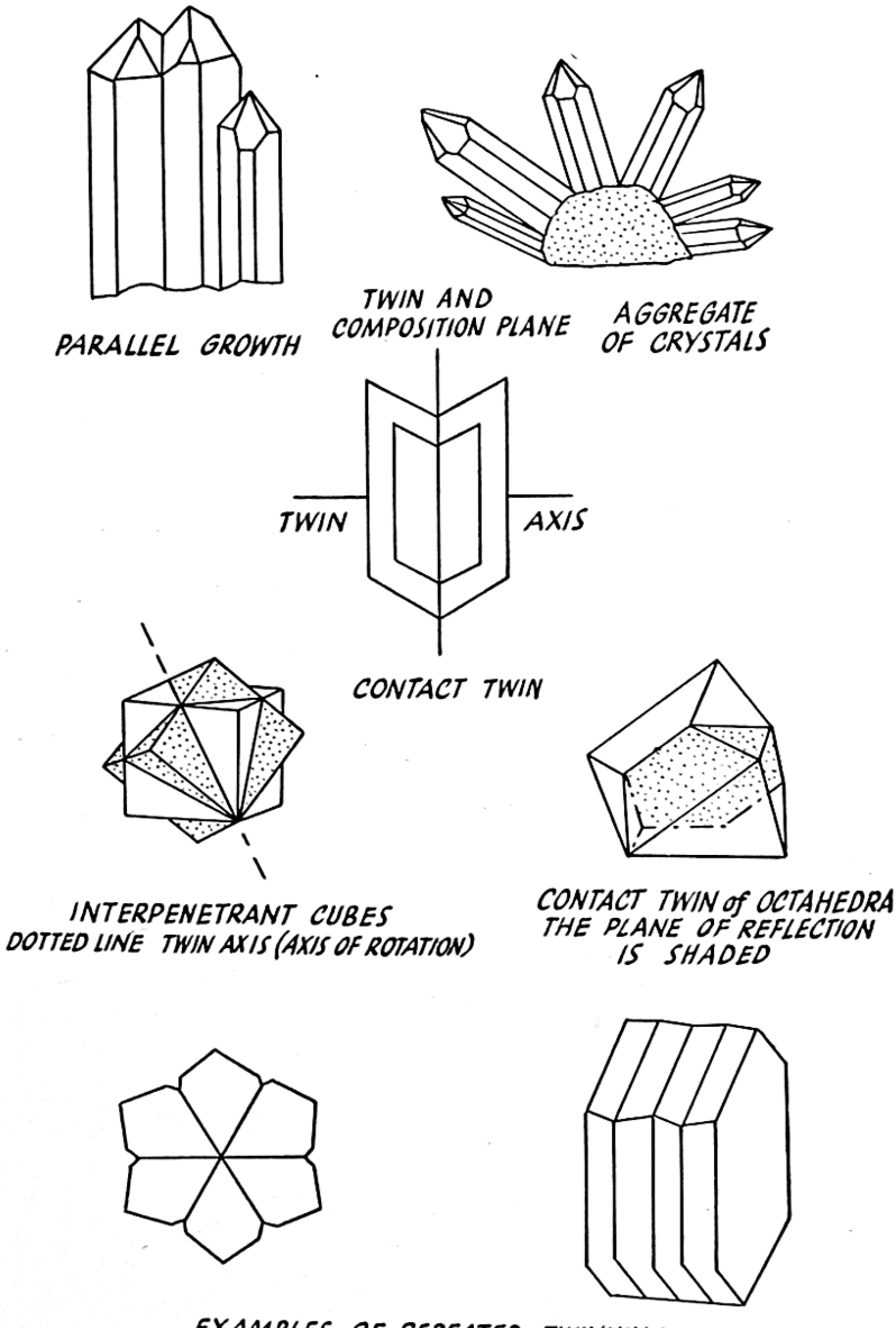


Fig. XI, 9.—Some Combinations of Crystals

Table III—SILICA

Name	*Composition*	*Common Form*	*Cleavage*	*Colour*	*Other Diagnostic Features*
Quartz	SiO_2	Hexagonal prism capped with rhombohedra. Also massive	None	White when pure. Amethyst the purple variety, also Milky, Smoky and Rose Quartz	Vitreous lustre. Hardness 7
Chalcedony	Mixture of Quartz and Opal	Usually mammillated or botryoidal	None	White or grey. Agate shows colour banding	Waxy lustre
Opal	SiO_2, nH_2O	Amorphous	None	Play of colour, very brilliant in the gem varieties	Hardness 6

Table IV
THE CHIEF ROCK-FORMING SILICATE MINERALS OF IGNEOUS AND METAMORPHIC ROCKS

Name	*Composition*	*Common Form*	*Cleavage*	*Colour*	*Other Diagnostic Features*
Orthoclase Feldspar	K_2O, Al_2O_3, $6SiO_2$	Monoclinic crystals, often simply twinned Also massive	Perfect basal and less perfect ‖ (010)	White or reddish	Moonstone is an opalescent variety of Orthoclase
Microcline Feldspar	Similar	Triclinic crystals, but often massive	Similar	Bright green (Amazon Stone)	Vitreous lustre
Plagioclase Feldspar	Isomorphous mixture of Na_2O, Al_2O_3, $6SiO_2$ (Albite) and CaO, Al_2O_3, $2SiO_2$ (Anorthite)	Triclinic crystals, but often massive	Similar	White or greyish	The multiple twinning is often visible on natural or broken faces

Pyroxene (Augite)	Silicate of Ca, Mg, and Al	Monoclinic crystals with 8 sides in plan and 2 at ends, sometimes twinned	Prismatic Two cleavages at 89°	Black	—
Amphibole (Hornblende)	Silicate of Mg, Al and Fe, with Al, Na and K	Monoclinic crystals with 6 sides in plan and 3 at ends, sometimes twinned	Prismatic Two cleavages at 124°	Black	—
Muscovite (White Mica)	Silicate of Mg, Al, K and H	Six-sided tabular crystals (Monoclinic but pseudo-hexagonal) Also in large plates	Very perfect basal	White	Pearly lustre, very thin laminae
Biotite (Black Mica)	Silicate of Mg, Al, K, H and Fe	Similar	Similar	Black	Splendent lustre, very thin laminae
Olivine	$2(Mg, Fe)O, SiO_2$	Prismatic, Orthorhombic crystals	Poor	Green	Peridot is a pale green gem variety
Serpentine	$2H_2O, 3MgO, 2SiO_2$	Massive, sometimes fibrous	Poor	Shades of green, red or white, often appearing veined and sometimes brecciated	Greasy lustre, hardness 3, sometimes slightly soapy to the touch
Topaz	$Al_2SiO_4F_2$	Prismatic Orthorhombic crystals	Perfect basal	Yellow	—
Zircon	ZrO, SiO_2	Prismatic Tetragonal crystals	Poor	Colourless or pale yellow	Adamantine lustre

Table V

THE SILICATE MINERALS CHARACTERISTIC OF METAMORPHIC ROCKS

Name	*Composition*	*Common Form*	*Cleavage*	*Colour*	*Other Diagnostic Features*
Andalusite	Al_2O_3, SiO_2	Prismatic Orthorhombic crystals	Good, prismatic	Pearl grey	The variety Chiastolite shows dark impurities often in a cruciform pattern
Asbestos	Silicate of Ca, Mg and Fe	Very long fibres	Perfect ∥ (110)	Greenish	Commercial Asbestos also includes the fibrous forms of Serpentine. Fire resisting
Beryl	BeO, Al_2O_3, $6SiO_2$	Hexagonal prisms, also massive	Poor	Emerald Green (gem emerald), pale green (gem aquamarine), yellowish white	White varieties opaque
Cordierite	Silicate of Al, Fe, Mg, with water	Short pseudo-hexagonal Orthorhombic crystals	Poor ∥ (010)	Blue, the crystals often show varying shades from different directions	—
Epidote	Silicate of Al, Ca and Fe with water	Elongate Monoclinic crystals	Perfect basal	Dark Green	Vitreous lustre

Garnet	$3\left\{\begin{matrix}Ca\\Mg\\Fe\\Mn\end{matrix}\right\}O, \left.\begin{matrix}Fe_2\\Al_2\\Cr_2\end{matrix}\right\}O_3, 3SiO_2$	Rhombicdodecahedra, trapezohedra or combination of these forms	None	Green in Lime Garnet, Grossular $3CaO, Al_2O_3, 3SiO_2$, Deep red in Almandine (Precious Garnet) $3FeO, Al_2O_3, 3SiO_2$	—
Idocrase	Silicate of Ca and Al	Tetragonal prisms capped by pyramids	Poor	Brown or black	—
Kyanite	Al_2O_3, SiO_2	Thin blade-like Triclinic crystals	Pinacoidal	Light blue	Rather pearly lustre on cleavage faces
Sillimanite	Al_2O_3, SiO_2	Needle-shaped Orthorhombic crystals	Poor ‖ (010)	Brown or grey	—
Staurolite	Silicates of Fe and Al	Prismatic Orthorhombic crystals, often twinned	Poor ‖ (010)	Reddish or yellowish-brown	Interpenetrant twins typical
Talc	$3MgO, H_2O, 4SiO_2$	Massive with foliated structure or in flakes	Highly perfect	Silvery white or greenish	Hardness 1, feels greasy, pearly lustre
Tourmaline	Boro-silicate of Aluminium	Bluntly terminated Hexagonal prisms	Poor	Black (schorl), green or red, often shows zoning	Vertical striations common

TABLE VI

METALLIC MINERALS

Name	*Composition*	*Common Form*	*Cleavage*	*Colour*	*Other Diagnostic Features*
Stibnite	Sb_2S_3	Columnar masses	Perfect	Lead grey	Iridescent, but apt to tarnish easily. Hardness 2
Orpiment	As_2S_3	Foliated and massive	Perfect	Lemon yellow	Pearly lustre on cleavage faces, otherwise dull
Realgar	AsS	Massive	Poor	Orange red	Resinous lustre
Native Copper	Cu	Massive or arborescent	None	Copper red	Heavy S.G. 8·8
Copper Pyrites	Cu_2S, Fe_2S_3	Usually massive	Poor	Brass yellow, often tarnished or iridescent (Peacock Copper)	Hardness 3·5–4 (cf. Iron Pyrites). Does not spark with steel
Malachite	$CuCO_3$, $Cu(OH)_2$	Usually mammillated	Perfect basal in crystals	Bright green, often banded	—
Azurite	$2CuCO_3$, $Cu(OH)_2$	Usually massive	Poor	Azure Blue	—

Native Gold	Au	Cubic, but usually as detrital grains, sometimes as nuggets, also as threads in veins	None	Yellow	Easily cut with knife, very heavy, S.G. 12 +
Magnetite	Fe_3O_4	Octahedra, also massive and granular	Poor	Iron black	Black streak, strongly magnetic
Haematite (Kidney Ore)	Fe_2O_3	Reniform masses with fibrous radiating structure	None	Cherry red	Cherry-red streak, silky lustre on fibrous faces
Specular Iron	Fe_2O_3	Rhombohedra	Poor, rhombohedral	Black	Cherry-red streak, splendent metallic lustre
Limonite	$2Fe_2O_3$, $3H_2O$	Mammillated masses with fibrous radiating structure	None	Black glaze on brown	Yellow-brown streak, dull submetallic lustre
Iron Pyrites	FeS_2	Cubes (often striated) and pyritohedra, also massive	Very poor	Bronze yellow	Hardness 6·5, splendent metallic lustre, strikes sparks with steel

TABLE VI—*Continued*

METALLIC MINERALS

Name	*Composition*	*Common Form*	*Cleavage*	*Colour*	*Other Diagnostic Features*
Marcasite	FeS_2	Nodules with radiating structure	Very poor	Paler yellow than pyrites	Prone to decompose to a white powder
Mispickel	FeAsS	Orthorhombic prisms with horizontally striated (011) faces	Perfect prismatic	Silver white tarnishing to steel grey	If struck by steel emits sparks and a smell of garlic
Cinnabar	HgS	Rhombohedra, but usually massive	Perfect, prismatic	Cochineal red	Scarlet streak, heavy S.G. 8·1
Galena	PbS	Cubes, also massive	Perfect, cubic	Lead grey	Heavy S.G. 7·5, Lead-grey streak, metallic lustre
Cassiterite (Tinstone)	SnO_2	Tetragonal prisms and pyramids. Waterworn in Stream Tin from placer deposits	Very poor	Black	Brilliant adamantine lustre on crystals, pebbles dull. Heavy S.G. 7
Blende (Black Jack)	ZnS	Tetrahedra and rhombic-dodecahedra	Perfect	Black or Brown	Crystals have adamantine lustre, but massive forms have a resinous lustre

TABLE VII—NON-METALLIC MINERALS (G = Chief Gangue Minerals)

Name	*Composition*	*Common Form*	*Cleavage*	*Colour*	*Other Diagnostic Features*
Corundum	Al_2O_3	Barrel-shaped Hexagonal crystals	Poor basal parting	Dull grey. Gem varieties include rubies and sapphires	Hardness 9
Spinel	MgO, Al_2O_3	Octahedra or rhombicdodecahedra. Often twinned	—	Red, brown	Hardness 8
G. Barytes	$BaSO_4$	Flat Orthorhombic crystals, also massive	Perfect, basal and (110)	White tinged with yellow	Heavy-spar, S.G. 4·5
G. Calcite	$CaCO_3$	Nail-head spar, flat rhombohedra on Hexagonal prism Dog-tooth spar, scalenohedra on Hexagonal prism Also fibrous and massive, etc.	Perfect, rhombohedral	White	Hardness 3 (scratched by steel)
Aragonite	$CaCO_3$	Orthorhombic prisms, often giving a pseudo-hexagonal appearance owing to repeated twinning	Poor	White	Slightly harder than Calcite
Dolomite	$CaCO_3$, $MgCO_3$	Rhombohedra, often with curved faces	Perfect, rhombohedral	Honey colour	—

TABLE VII (*Continued*)—NON-METALLIC MINERALS

Name	*Composition*	*Common Form*	*Cleavage*	*Colour*	*Other Diagnostic Features*
Gypsum	$CaSO_4, 2H_2O$	Monoclinic crystals (Selenite), often twinned as arrow-head or swallow-tail types. Also massive (Alabaster) and fibrous (Satin-spar)	Perfect, ‖ (010)	Colourless	Hardness 2, pearly lustre on cleavage and (010) faces, on other faces vitreous lustre
Apatite	$3Ca_2P_2O_8$, $Ca\left\{\begin{matrix}Cl_2\\F_2\end{matrix}\right.$	Hexagonal prism with stumpy pyramid	Poor basal partings	Pale green with tinge of red	Subresinous lustre
G. Fluor-spar	CaF_2	Cubes, also massive	Perfect, octahedral	Purplish (Blue John), many other shades as well	Hardness 4
Diamond	C	Octahedral crystals, but water-worn from placers	Perfect, octahedral	White or colourless	Hardness 10, most brilliant adamantine lustre
Graphite	C	Laminar masses	Perfect	Black to grey	Hardness 1, black shining streak, metallic lustre
Rock Salt	NaCl	Cubes or massive	Perfect, cubic	Colourless if pure	Taste
Sulphur	S	Orthorhombic pyramids and also massive	Poor	Sulphur yellow	Resinous lustre

G = Chief Gangue Minerals

plan, being composed of aggregates of twins with the composition planes radiating from a point. In the more obvious type of multiple twinning, the composition planes are all parallel.

Pseudomorphs

The identification of a mineral should not be based on crystallography alone, but should be confirmed by its physical characters. A pseudomorph is a crystal having the form characteristic of one mineral but composed of another mineral. Owing to weathering and other causes, a crystal of one mineral, for example a cube of pyrites, may be completely altered, without any change of shape, to another mineral, limonite. The cube is then said to be a pseudomorph of limonite *after* pyrites, for it has the composition and physical properties of limonite, but the shape of a typical crystal of pyrites.

In Tables III–VII are summarized the chief physical and crystallographic properties diagnostic of the commoner minerals. Each mineral has a unique combination of properties. It is very unsafe to base an identification on one property alone, all those which can be recognized from the specimen should be taken into consideration.

Minerals can be classified in several ways. Probably the most scientific method is according to chemical composition, the oxides, carbonates, etc., being grouped together. Another way is according to the elements of which the minerals are compounds. The method adopted here is to separate the rock-forming silicate minerals into those that occur in both igneous and metamorphic rocks and those that are characteristic of metamorphic rocks. The non-silicate minerals have been divided into 'metallic' and 'non-metallic' groups. Admittedly the distinction cannot be defined precisely, but it is a convenient one. The metallic minerals include the more important ores and are usually heavy and of metallic appearance especially as regards lustre. The non-metallic minerals, on the other hand, are usually lighter both in colour and weight and include the common gangue minerals.

The Use of the Petrological Microscope

The minerals building up rocks are usually too small to be identified by the methods given above. A thin section of the rock must be examined under a petrological microscope.

To make a thin section of a rock, a slice is cut with a rotating

disc armed with diamond dust. One side of the slice is ground smooth, using varying grades of carborundum powder as abrasive. The prepared side is cemented by Canada Balsam to a microscope slide and the other side of the slice is then ground away, until the section is thin enough (about 1/1000 of an inch) to be completely transparent. Finally a cover slip is cemented on with Canada Balsam to preserve the slide. Slide-making requires a considerable amount of skill, particularly in the final stages of grinding. Soft rocks may have to be hardened by impregnation with a synthetic resin as otherwise they will go to pieces during the grinding.

The slide is now ready to be placed on the stage of a *petrological microscope*, which differs from other microscopes in having a rotating stage with means for measuring the angle of rotation and by having attachments for polarizing the light, which is reflected by a mirror through the slide and up the tube of the microscope.

Minerals can only be identified with certainty if *plane polarized light* is used. Ordinary light consists of waves vibrating in all planes at right angles to the direction in which the light is travelling. The waves of plane polarized light, however, vibrate in one plane only (Fig. XI, 10). In the petrological microscope, two specially cut crystals of Iceland Spar (the transparent variety of calcite), or pieces of synthetic 'Polaroid', are placed above and below the stage. The lower of these polarizing devices or 'nicols' (after the discoverer, William Nicol, 1828) is rotatable and is placed below the stage. The upper nicol or analyser is firmly mounted above the objective lens system in a little box, so that it can be pushed in and out of the microscope tube.

If the lower nicol or polarizer is rotated without a slide on the stage and the analyser pushed into the tube, then twice in every complete revolution the field will appear black. This is because the nicols are crossed with their vibration directions at right angles to each other and therefore no light can be transmitted past the upper nicol. Before using a petrological miscroscope one should always check that the nicols are crossed, as otherwise the optical system will not be properly adjusted. The polarizer should be rotated, if necessary, until the field is black.

If a slide is now placed on the stage and examined in plane polarized light, i.e. with the analyser pushed out, parts of the slide will appear colourless and others will be coloured. If the stage is rotated, most coloured minerals will show a change of colour or *pleochroism*; in some cases very pronounced (for example in most sections of biotite from a straw yellow to a deep brown), but in

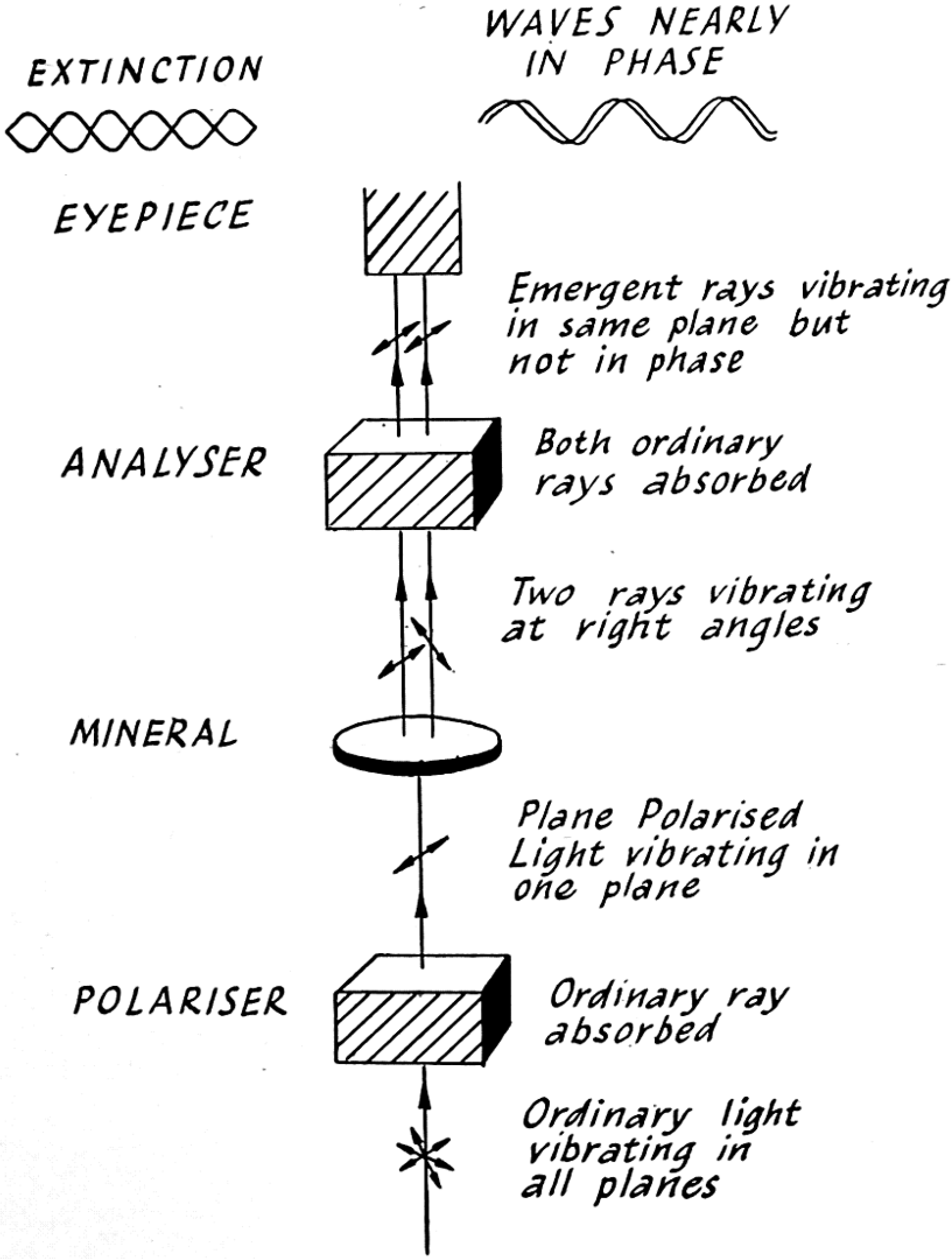


Fig. XI, 10.—Passage of Light Through a Petrological Microscope

feebly pleochroic minerals like augite, the change is scarcely perceptible, whilst certain coloured minerals, for example basal sections of biotite, are non-pleochroic and show no change of colour on rotation. Pleochroism is shown by those minerals that absorb the components of white light differently in different directions. At every 180° the mineral will be in the position of minimum absorption and will then appear of lightest colour.

If the nicols are crossed, both the coloured and the uncoloured minerals in plane polarized light will now be showing colours, varying from pale greys to the most brilliant greens, reds and purples. These *interference colours* are due to the plane polarized light, which reached the mineral from the polarizer, being resolved into two rays, the ordinary and the extraordinary rays, vibrating at right angles to one another at differing frequencies. Each of these rays will be resolved into ordinary and extraordinary components in the analyser, which is so made that the ordinary rays do not emerge from it, whilst the two extraordinary rays that do are vibrating in the same plane, but with their wave motions out of phase (*see* Fig. XI, 10). As the slide is rotated, the phase difference between the two rays passing to the eye is constantly changing. At every 90° of rotation, the two rays are completely out of phase and the mineral is in the position of *extinction*, appearing black, but at 45° to this position, when the two rays are in phase with each other, the mineral will be showing its brightest colours.

The interference colours of a mineral depend on its thickness and orientation as well as on the nature of the mineral. The effect of thickness can be seen by pushing slowly through a slot in the tube of the microscope a wedge made of quartz. As the wedge is inserted it shows bands of colour at right angles to its length, each colour appearing when the wedge is of a certain thickness. The colour bands appear in the following order: black, grey, white, yellow, orange, red and then Newton's scale of colours is repeated with indigo, blue, green, yellow, orange, orange-red changing to indigo, greenish-blue, green, greenish-yellow and dull purple and so on. The bands of reddish hue are taken to divide the sequence of colours into orders, black to red being the first order, the bright colours indigo to orange-red the second order, whilst the third order colours are somewhat fainter. The sequence of the higher orders is the same with the colours becoming increasingly fainter and more difficult to recognize. It is more precise to describe the interference colours of a mineral in terms of their order on this scale rather than by using terms like gaudy, dull, etc.

If the mineral possesses cleavage, shown by well-marked parallel cracks, its *extinction angle* is often of considerable diagnostic value. This is measured by rotating the stage in plane polarized light, until the cleavage of a selected crystal is parallel to one of the cross wires in the eye-piece of the microscope. These cross wires are set parallel to the vibration direction of the nicols. Read the angle against the index of the scale and then cross the nicols. If the mineral is not now in extinction (*straight extinction*), rotate the stage through the minimum angle necessary to produce extinction. Read the scale again and the amount of rotation is the extinction angle. But basal sections of some minerals, augite, hornblende, etc., show two cleavages and have *symmetrical extinction* with the cross wires bisecting the angle between the cleavages.

The minerals in an igneous rock are lying haphazardly with their crystallographic axes pointing in all directions. As cleavage and other properties used in the optical study of minerals are related to the position of the crystallographic axes, it follows that a thin section will cut most crystals at an oblique angle to their axes. Only very occasionally will a mineral be cut exactly along either its basal or its vertical plane. A basal section of a Tetragonal or Hexagonal mineral will not show interference colours, but will remain black on rotation. The axes of these basal sections are of equal length. Any section of a Cubic mineral is also *isotropic* and is thus easily distinguished from anisotropic minerals, which show interference colours.

This haphazard arrangement of minerals also explains the fact that there may be considerable differences in the extinction angles measured in sections of what are clearly the same mineral. It is therefore necessary to examine a number of sections of any one mineral and record the different values obtained. In the same way the *shape* of a mineral will be determined by its orientation, provided that it was one of the first minerals to crystallize and therefore had room in which to develop its true crystallographic form. Minerals that crystallized last had to fill in what space was available and therefore may have very irregular outlines. Well-formed minerals, bounded by natural crystal faces, are called idomorphic or *euhedral*, irregularly shaped minerals are *anhedral*.

To identify minerals, it is necessary to search the slide for either basal or vertical euhedral sections and then to study shape, pleochroism, interference colours, cleavage and extinction angle.

The *twinning* of minerals can be seen best under crossed nicols, for when one-half of the twin is in extinction, the other will be showing its characteristic interference colours. In advanced work,

the different feldspars, especially the plagioclases, are identified mainly by studying their twinning.

Certain minerals, such as the micas and olivine, show a markedly pitted surface, others such as quartz and the feldspars a smooth surface. The *surface relief* of a mineral depends on the difference between the refractive index of the mineral and that of the Canada Balsam in which it is mounted. When a ray of light travels from one medium to another, it will move with a different velocity and will be bent or refracted (provided that it is not totally reflected) at the surface of contact. In H. G. Wells' story the man made himself invisible by making the refractive index of his body the same as that of air, so that light rays passed through him without being affected. The greater the difference of the refractive index of a mineral from Balsam, the more strongly will the effects of the grinding process be shown.

The *Becke* test is a quick method of determining whether the refractive index of a mineral is greater or less than that of Balsam. Select a mineral in contact with Balsam, probably near the edge of the slide, and fit a high power objective. If the mineral is just out of focus, it will be surrounded by a ring of light, which will move into the medium of higher density (either the mineral or Balsam) as the objective is raised, or *vice versa* as it is lowered. With the exception of nosean, hauyne and the feldspars, the refractive indices of the minerals listed in Tables VIII and IX are all higher than that of Balsam. In the same way the relative refractive indices of any two minerals in contact can be determined.

Certain minerals, such as augite, show a colour banding or *zoning* parallel to the crystal faces, others may be altered to fibrous secondary minerals. In the micas this alteration takes place along the perfect basal cleavage, in olivine along curved cracks.

In the tables on pages 163–5 are summarized the optical characters of the common minerals of igneous rocks. As in the identification of minerals in the hand specimen, it is the combination of characters which is diagnostic. Several minerals show straight extinction but only biotite combines this with strong pleochroism, second-order interference colours and marked surface relief. The shapes given are for euhedral crystals and these must be sought for but extinction angle, cleavage, twinning, etc., can be seen equally well in anhedral minerals.

Table VIII.—The Characters of Minerals in Thin Section

Coloured in Plane Polarized Light

Name	Shape	Pleochroism	Cleavage	Extinction Angle	Interference Colours	Other Diagnostic Features
Biotite	Basal: Hexagonal	Non-pleochroic in dark brown	None	None	Isotropic	Strong surface relief. Often altered to green chlorite along cleavages
	Vertical: Parallel sides, jagged ends	Strong straw-yellow to dark brown	Perfect, single	Straight	2nd order, but usually masked by strong absorption	
Hornblende	Basal: six-sided	Non-pleochroic in green	2 cleavages at 124°	Symmetrical	2nd order colours, but usually masked by absorption	Simple twins rather rare
	Vertical: variable	Fairly strong in green or brown	Single	0° to 24°		
Augite	Basal: eight-sided	Non- or feebly pleochroic in pale green, brown or pink	2 cleavages	Symmetrical	2nd and 3rd orders	Simple twinning and Zoning not uncommon
	Vertical: variable		Single	0° to 45°		
Olivine	Roughly six-sided	Colourless if fresh, but non-pleochroic yellow or green where altered to serpentine	Prominent curved cracks, not a true cleavage	None	Bright 2nd and 3rd orders when fresh, but little change if serpentinized	Fresh olivine shows strong surface relief. Absence of twinning and alteration to serpentine very characteristic

TABLE VIII (*continued from previous page*)

Name	*Shape*	*Pleochroism*	*Cleavage*	*Extinction Angle*	*Interference Colours*	*Other Diagnostic Features*
Nosean	Six-sided, but often deeply indented	Very pale yellow-grey with distinct dark margin	Rarely visible	Isotropic	Isotropic	—
Hauyne	Similar	Sky blue with dark margin	Rarely visible	Isotropic	Isotropic	—
Garnet	Six-sided, but usually distinctly rounded	Non-pleochroic, colourless, pink or brown	Cleavages rarely seen, cracks common	Isotropic	Isotropic	Clear outlines and marked surface relief
Sphene	Double wedge-shaped	Slight pleochroism in greyish-brown	Rarely visible	None	No change of colour on crossing nicols	Strong surface relief
Tourmaline	Stout prisms, but triangular in basal sections	Very strong pleochroism in blues and browns. Basal sections non-pleochroic	None, but basal fractures sometimes visible on vertical sections	Parallel to length	Strong, 2nd order	Basal sections sometimes zoned
Magnetite	Small and variable	Black	None	Opaque	Opaque	Steel grey by oblique reflected light

Table IX.—The Characters of Minerals in Thin Sections

Not Coloured in Plane Polarized Light

Name	*Shape*	*Cleavage*	*Extinction Angle*	*Interference Colours*	*Twinning*	*Other Diagnostic Features*
Muscovite	Like biotite	Like biotite	Straight	Bright 2nd order colours	None	Strong surface relief and interference colours
Quartz	Variable, usually filling in spaces between other minerals	None	None	1st order, grey to white Basal sections isotropic	None	Lines of minute inclusions and bubbles
Orthoclase	Variable	Two, or no cleavages visible	Straight and oblique	1st order, grey-white or yellow	Simple, parallel to or oblique to length	Often altered to dusty Kaolin, visible in P.P.L.
Microcline	Variable	Like orthoclase	Like orthoclase	Weak	Two sets at right angles	"Shepherd's plaid" effect distinctive
Plagioclase	Variable, but often in laths	Perfect ‖ (001), others less so	Variable	1st order greys or whites	Repeated	—
Perthite	Variable	Like plagioclase	Variable	1st order greys or whites	—	Intergrowths with microcline give "watered silk" in "shepherd's plaid"
Leucite	Eight-sided	None	None	May be isotropic or 1st order greys	In 6 directions, with strong illumination	Inclusions usually arranged either radially or concentrically
Apatite	Basal: Six-sided Vertical: needles	Imperfect basal	Straight	1st order greys, basal sections isotropic	None	Small colourless crystals with clearly marked outlines

CHAPTER XII

Commoner Igneous and Metamorphic Rocks and their Economic Uses

THE nomenclature of igneous rocks is based on two variables, texture and composition. The texture of a rock is determined by its cooling history. Slow cooling produces a coarse and approximately even-grained rock, very rapid cooling an extremely fine-grained, perhaps even a glassy rock. But there are many rocks with large crystals (*phenocrysts*) of one or more minerals set in a fine-grained ground-mass. Such rocks of *porphyritic texture* must have passed through two stages of cooling; first the slow development of large crystals of the first minerals to form and then rapid chilling of the remaining magma, due often to intrusion into a new environment.

We therefore find that the coarse-grained rocks usually occur as batholiths or plutons, the fine-textured rocks as lava flows and those of intermediate texture as sills, dykes and other minor intrusions. But to classify the igneous rocks into plutonic (deep-seated), hypabyssal (minor intrusions) and extrusive types, as is sometimes done, means that the emphasis is placed on their mode of occurrence. It is sometimes very difficult to determine in the field whether a concordant igneous body is a sill and therefore hypabyssal or whether it is an extrusive lava flow. Alternatively a considerable difference in texture can often be observed across a thick sill or lava flow. It is much more scientific to use the terms coarse-, medium- and fine-grained in the strictly descriptive sense without any implication as to mode of occurrence. Mode of occurrence is a separate problem depending on the field relations and not primarily on the nature of the igneous rock in question.

To determine accurately the chemical composition of an igneous

rock requires elaborate and painstaking chemical analysis. The minerals, usually less than half a dozen in number, that make up a rock reflect, however, fairly closely the chemical composition of the magma from which they crystallized. These minerals can often be recognized in the hand specimen or, with greater precision, under the microscope. For field determinations and elementary microscope study, the mineralogical composition of a rock is therefore of fundamental importance in classification.

The minerals of igneous rocks can be divided into the felsic and mafic groups. The *felsic* minerals include the feldspars, the felspathoids (nosean, leucite, etc.) and silica (quartz), the *mafic* group the silicates of magnesia and iron (Fe), that is, the micas, pyroxenes, amphiboles and olivine. Rocks which are light in colour with a predominance of felsic minerals are often referred to as *leucocratic*, the dark types with an excess of mafic minerals as *melanocratic*.

The next stage is to consider the assemblage of minerals present and especially their content of silica. In the Acid Group, there is an excess of silica, shown by the presence of quartz crystals, but in the Basic Group the silica is normally combined with bases to form silicates and these silicates are often basic varieties of the feldspar, amphibole and pyroxene groups with low silica content. The Intermediate Group is transitional, with its more acid members containing small amounts of free quartz, and its more basic members minerals like olivine and the felspathoids, which seem to be incapable of forming in the presence of free quartz. The boundaries between the different groups are not clean-cut lines but are really zones of transition and, whilst typical rock-types can be placed accurately in their appropriate pigeon-hole, one sometimes comes across border-line cases.

Combining texture with mineralogical composition, we can recognize the main groups of igneous rocks as shown on page 168; the Intermediate Group being further sub-divided according to whether the feldspar is dominantly alkaline (orthoclase or microcline) or soda-lime plagioclase.

The Macroscopic Characters of the Commoner Igneous Rocks

Granite is a coarse-grained leucocratic rock with appreciable amounts of free quartz. A typical granite is even-textured, but porphyritic types are not uncommon. These include Cornish Giant Granite, with large white phenocrysts of orthoclase and Shap Granite from Westmorland, in which the orthoclase phenocrysts are

Table X

THE CLASSIFICATION OF THE IGNEOUS ROCKS

	Acid	*Intermediate Feldspar*		*Basic*	*Ultrabasic or Ultramafitic*
		Alkaline	*Soda-Lime*		
Coarse-grained	Granite	Syenite	Diorite	Gabbro	Peridotite, Serpentinite, etc.
Medium-grained	Microgranite	Micro-syenite	Micro-diorite	Dolerite	—
Fine-grained	Rhyolite, Obsidian	Trachyte	Andesite	Basalt	—
Specific Gravity	2·4–2·7	*c.* 2·8		2·9	3·0 or above
Characteristic Minerals	Free quartz, orthoclase the dominant feldspar, some mica (biotite and muscovite) and in more basic types a little hornblende or augite	Hornblende and feldspar dominant. In more acid types some quartz and biotite, and in more basic types perhaps some augite and/or felspathoids (hauyne, nosean and leucite)		Soda-lime plagioclase and augite dominant, usually with olivine and perhaps some hornblende or in more basic types some felspathoids	Little or no feldspar. Often almost monomineralic

of pinkish hue. A typical example of the more even-textured granites is the handsome reddish rock from Peterhead near Aberdeen.

Pegmatites. The margins of many granites are traversed by dykes of pegmatite, an extremely coarse-grained rock, composed essentially of quartz and feldspar, but often containing micas and other silicates. In some pegmatites the crystals of mica are several feet in diameter.

Aplites, also occurring as veins in granites, are very even-textured and usually fine-grained, quartz-feldspar rocks, having a sugary or saccharoidal appearance.

Both pegmatites and aplites must have formed at a late stage of the consolidation of a granite, from liquids rich in volatiles and therefore of low viscosity, so that they were able to penetrate along the fissures.

Pneumatolytic modifications of Granite. After the final consolidation of a granite magma gases may be released which travel along fissures and greatly modify the mineralogical composition of the rocks, either granite or country rock, with which they came into contact. *Greisening,* due to fluorine-charged gases, produces a rock composed essentially of white mica and quartz and often containing fluorine-bearing minerals, such as fluorite and topaz. *Tourmalinization,* due to boron-rich gases, attacks first the micas and then the feldspars with the development of black tourmaline (schorl). Reference has been made elsewhere (p. 124) to *Kaolinization,* which is mainly due to steam at a high temperature.

Microgranites are rocks of granite composition, made up of minerals which are clearly visible to the naked eye, but the average diameter of which is less than 1 mm. Porphyritic types are common, quartz-porphyries being perhaps the best known.

Granophyres are a group of microgranites in which the quartz is inter-grown in a very complex manner with the feldspar, producing, particularly in thin section, a hieroglyphic-like appearance.

Rhyolites typically contain small quartz crystals set in a groundmass too fine-grained to be differentiated with the unaided eye. They grade into the volcanic glasses, *Obsidian,* which is dense black and has a markedly conchoidal fracture and *Pitchstone,* which contains many minute crystals and is of variegated hue. Rhyolites often show a variety of textures. The *flow banded* rhyolites give one a most vivid impression of a suddenly chilled viscous liquid with lines of minute crystals eddying round the phenocrysts. *Sphaerulitic* rhyolites contain numerous centres of crystallization, round which spheres, sometimes several inches in diameter, have developed.

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The *Intermediate* Rocks, which are not nearly so common as either the acid or the basic rocks, show a considerably greater range of mineralogical composition. They can be divided into two main groups or clans, both including coarse-, medium- and fine-grained members. The Syenite Clan is essentially leucocratic, whilst the Diorite Clan is more melanocratic. Whilst the more acid types of syenites contain small amounts of free quartz, other syenites contain one or more of the felspathoid minerals. Such rocks are said to be *undersaturated*, for nepheline, in particular, is a silicate containing an unusually low percentage of silica and can only form in melts in which the amount of silica is insufficient to saturate all the bases. It is usually impossible to distinguish in the hand specimen the type of feldspar and felspathoids present. Thorough examination of a thin section is necessary and therefore the detailed description of the many varieties of Intermediate rocks is beyond the scope of this book.

Syenites occur as marginal facies of, or off-shoots from, granite masses and were most probably formed by reaction between the granite and its roof- or wall-rocks. Desilication, due to assimilation, has produced an intermediate rock and if limestone was assimilated, one that is undersaturated.

The Basic Rocks. The essential mineralogical feature of gabbros, dolerites and basalts is the dominance of pyroxene and one of the more basic plagioclases, but either quartz or, in the more basic types, pale green olivine may also occur in small quantities. If these are recognizable, one can be more precise in nomenclature by speaking of quartz-dolerite, olivine-basalt, etc.

Typically the basic rocks are melanocratic and are distinctly heavier than their acidic equivalents. *Gabbros* are coarse-grained melanocratic rocks with an appreciable content of mafic minerals. Olivine-gabbros are often considerably altered, the olivine changing to serpentine and the feldspars becoming cloudy with secondary minerals.

Dolerites show the same proneness to alteration and the term *diabase* is often applied to a much altered dolerite rock in which a few of the original minerals are present. *Basalts* are typically dark heavy fine-grained rocks, but they show a considerable range of texture, varying from distinctly porphyritic types to basalt glass or *tachylyte*, whilst rarely they may contain isolated quartz crystals, or in the undersaturated types, felspathoids. Basalts are the most widely distributed of all igneous rocks, for they build up not only the enormous lava plateaux and the great central volcanoes of the Hawaiian type,

but often occur as dykes, sills and other minor intrusions. The term *spilite* is often applied to basaltic rocks, showing pillow structure, but strictly speaking a rock should be named from its distinctive mineralogical composition and therefore a spilite is a basic lava containing albite feldspar and with numerous calcite-filled vescicles or small almond-shaped cavities formed by escaping gas and steam. Such a rock commonly, but not invariably, shows a pillow structure. Spilites have been poured out on the ocean floor and their distinctive mineralogical assemblage is due to the reaction of basaltic magma with salt water.

The *Ultrabasic* or *Ultramafitic* rocks consist essentially of mafic minerals only. The nature of pyroxenite is obvious, whilst *serpentinites* are deeply altered rocks, composed almost entirely of serpentine, and showing a streaked appearance in reds and greens.

The ultrabasic rocks are of rare occurrence, forming the lower parts of large intrusions. They must have been formed by the gravity differentiation of the densest and first formed crystals of a magma.

One group of rocks, which does not fit easily into the scheme of classification used here, are the *Lamprophyres*. These are dyke rocks and are always markedly porphyritic with large phenocrysts of a mafic mineral, often biotite, set in a ground-mass, which is usually considerably altered. The phenocrysts are usually deeply corroded, showing that they were attacked by the liquids which crystallized to form the ground-mass; it is therefore probable that the phenocrysts and the ground-mass had different origins and were not formed, as is the case with most other rocks, from the crystallization of a single body of magma.

Pyroclasts are mostly developed in the vicinity of the more viscous (acidic) volcanoes. They include a wide range of textures, grading from agglomerates through volcanic breccias into ashes. The *agglomerates* are composed of the material thrown out immediately around the vent. They are extremely ill-graded, being characterized by large angular fragments, sometimes up to several tons in weight, of lava and the country rocks through which the vent was drilled. The term *volcanic breccias* is often given to the finer-grained of the agglomerates, still obviously fragmentary, but without much coarse material. Both agglomerates and volcanic breccias sometimes contain volcanic bombs, pear-shaped pieces of highly vescicular lava, which, while still molten, were blown out of the vent and shaped by their rapid fall through the air.

The finest material, less than 1 mm. in diameter, ejected from a volcano, may be carried by the winds and deposited a long distance away to form beds of *volcanic ash*. Such ashes often contain fragments of volcanic glass or of lava or even well-shaped crystals, formed in the lava before the explosion occurred. These ashes often show many of the minor structures typical of sedimentary rocks, for if the ejected material fell into water, it would have been subjected to the same sorting, etc., as a water-deposited sediment. A high proportion of volcanic debris is clear evidence that such a rock must be of pyroclastic origin.

Owing to the way in which they are deposited, pyroclasts are usually very porous. Ashes, which have been lithified, either by percolating ground water or by the weight of other rocks, are termed by some *tuffs*, but there are many who regard the terms ash and tuff as synonymous, adding, if necessary, the prefix compact or uncompacted. Another result of the porous nature of volcanic ashes is that they are very prone to post-depositional or diagenetic changes, especially to silicification, when a hard flinty rock, termed a *halle-flinta*, is produced. It is therefore often impossible to classify the fine-grained pyroclasts genetically into rhyolite-tuff, andesite-tuff, basalt-tuff, etc., for the diagenetic changes have completely masked the original chemical composition of the volcanic material.

The Economic Uses of Igneous Rocks

Great quantities of igneous rocks are quarried either for use as building stone or as road stones. A building stone must be fairly easily worked and should be attractive in appearance. Most igneous rocks can be cut, shaped and polished (if necessary) without undue difficulty, so that appearance is usually the deciding factor. Preference is naturally given to the lighter-coloured rocks and therefore owing to their sombre look, basic and ultra-basic rocks are used relatively little, though serpentinite, with its variegated hues, is quite popular as a decorative stone for interiors. Granites and syenites, coarse-grained and of pleasing colour, are well favoured as building stones and it is usually the porphyritic types, such as the Giant Granite of Cornwall or the Shap Granite, which are preferred to the more even-grained varieties. One widely used decorative stone, Laurvikite, a variety of Syenite from Norway, contains large bluish feldspars, which show on a polished surface a beautiful play of colours or schillerization.

One asset of igneous rocks is that, provided sound stone has been

selected, they are resistant to the vigorous chemical weathering that takes place in the smoke-laden air of towns.

Basic rocks are, however, much more in demand as road stones than are the more acid rocks, for they are usually tough and durable. Granites, particularly the porphyritic types, do not wear so well, for their minerals are not so tightly interlocked. Quartz porphyries and the tougher rhyolites are usually satisfactory.

THE METAMORPHIC ROCKS

The changes produced by metamorphism will depend partly on the chemical composition of the rock affected and partly on the temperatures and pressures to which it has been subjected. Metamorphism of a pure quartz rock (a sandstone) or of a pure limestone, can only produce a more compact recrystallized rock, a quartzite or a marble of the same mineralogical composition. But if an impure sedimentary rock or an igneous rock, composed of a mixture of silicate minerals, is metamorphosed, a rock of different mineralogical composition will be produced. For example, during the metamorphism of a rather sandy limestone, the calcite and silica combine to form crystals of a lime silicate mineral, wollastonite, as under:

$$CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2$$

whilst in a sandy dolomitic limestone, the greenish mineral, forsterite, is formed:

$$2CaCO_3, MgCO_3 + SiO_2 \rightarrow 2CaCO_3 + MgSiO_4 + 2CO_2$$

Many marbles used for ornamental purposes originated from impure limestones, and owe their attractiveness to the silicate minerals which they contain. A good example is the Connemara Marble of Ireland, originally a forsterite-marble, in which the forsterite has been subsequently altered to serpentine ($2H_2O$, MgO, $2SiO_2$), producing a whitish rock pleasantly streaked with green.

In the same way an igneous rock will be altered to a rock containing crystals of such typically metamorphic minerals as garnet and kyanite. The mineralogical changes may not be a simple case of rearrangement of the chemical constitution of the original rock, for often there has been either the addition or the removal of material.

With complicated changes of this type, it is often an extremely

difficult matter to reconstruct the nature of the rock which has been metamorphosed or the stages through which it has passed, including any effects of weathering before metamorphism; but this is a matter which cannot be taken further here.

The Macroscopic Characters of the Commoner Metamorphic Rocks

The main types of Metamorphic Rocks are described below. Greater precision is gained by prefixing the names of the chief minerals present, e.g. garnet-mica-schist, sillimanite-gneiss, forsterite-marble, etc., though in the finer-grained types it may not be possible to recognize these minerals in the hand specimen.

Quartzite, a hard white rock composed of closely interlocking quartz grains.

Granulite, an equigranular rock made up of tightly interlocking grains of quartz and feldspar.

Marble, a recrystallized rock, composed entirely or largely of interlocking crystals of calcite. Pure marble and pure quartzite are both glistening white rocks, but marble can be scratched by steel, quartzite cannot.

Slate, originally an argillaceous rock, which has been subjected to pressures sufficient to produce reorientation of the flaky minerals, so that new planes of easy splitting or cleavage are developed. The cleavage is usually at a high angle to the original bedding, so that fossils are distorted or completely destroyed. Slates are sometimes crossed by thin layers of coarse material, which has resisted the cleavage. Such bands, often of a different colour from the rest of the slate, show the relation between the original bedding of the rock and the cleavage direction (Fig. X, 10). If slates are subsequently thermally metamorphosed they become spotted, owing to the development of new (high temperature) minerals.

Phyllite is a more intensely metamorphosed slaty rock characterized by the presence of numerous flakes of white mica and chlorite, giving it a glistening appearance.

Schists. Mica-schists are the end members of the series mud—shale or mudstone—slate—phyllite—mica-schist. More intense pressure and changes due to fluids migrating through the rock, have caused the development of platy minerals, all lying parallel, so that the rock is foliated, with numerous closely spaced planes of schistosity, along which it splits easily. These surfaces are, however, usually more irregular and curving than the cleavage planes of slate. There are many other varieties of schists, including quartz-schists derived from

the metamorphism of impure sandstones, hornblende-schists from basic rocks and talc-schists from ultra-basic rocks.

Gneisses are much more coarsely foliated than schists. They are markedly banded with the bands composed of different minerals, e.g. an alternation of quartzose and felspathic layers with the mafic minerals usually separately concentrated. Gneisses also have a more streaked-out appearance than schists, and often contain eyes or 'augen' of more granitic composition, round which the other minerals have flowed. They have been so altered that the original nature of the rock is often very debatable, but if it can be determined, the term 'ortho-gneiss' is applied to gneisses which originated from igneous rocks and 'para-gneiss' to those which were originally sediments.

Hornfels are hard fine-grained rocks, often with a flinty appearance, developed in the inner zones of metamorphic aureoles. Shales give rise to dark hornfels, carrying wollastonite, lime garnet, etc., whilst the hornfels derived from basic igneous rocks are usually greenish in hue and rich in feldspars and amphiboles and pyroxenes.

Mylonites are crushed rocks developed along major thrust planes. A sequence can be traced from a fault-breccia with angular fragments of uncrushed rock set in pulverized rock dust, through a crush-conglomerate, in which the boulders have been elongated, to a true mylonite composed almost entirely of rock dust, which has often been fused owing to the heat generated by the friction of the moving rock masses.

Eclogites are coarse-grained heavy rocks, composed essentially of green pyroxene and red garnets. Certain eclogites are undoubtedly of metamorphic origin, for they occur as lenticles in schists, but other eclogites, interbanded with ultra-basic igneous rocks, appear to be true igneous rocks, which have consolidated at a considerable depth under high pressure.

The Economic Uses of the Metamorphic Rocks

Except for quartzites, the metamorphic rocks are usually unsatisfactory as road stones. Marbles are little harder than the more compact limestones, whilst foliated and cleavaged rocks are traversed by so many planes of weakness that they soon go to pieces. Hornfels are tough, but rather brittle, and like certain quartzites may contain closely spaced shear or thrust planes, along which the rock may fail under stress.

Quartzites are usually too difficult to work and too uniform in appearance to be used as building stones. Marble, on the other hand,

is easily worked and is extensively used as a decorative stone and for statuary. A pure marble, like that from Carrara in Italy, is monotonously white. Many of the impure marbles, such as the Connemara stone of Ireland, have a much more attractive appearance, due to the coloured silicates which they contain, whilst the stresses to which the marbles have been subjected often produce fantastically brecciated and variegated rocks. In Scandinavia, considerable use is made of certain gneisses, which are tough enough to withstand cutting and polishing. They produce, to the geological eye, a most attractive decorative stone, in which the structures due to metamorphism are shown to advantage.

The fissile nature of slates makes them ideal roofing material, but unfortunately the expense of quarrying them is often very great, for only highly cleaved material can be split into sufficiently thin slabs. In the slate mines of North Wales, the seams of high quality slate are separated by considerable thicknesses of poorly cleaved material, so that the quantity of waste material that has to be shifted is many times that of the slate that is obtained.

CHAPTER XIII

Commoner Sedimentary Rocks and their Economic Uses

IT is often very difficult to deduce the environment in which sedimentary rocks were formed. It is therefore impossible to classify them genetically, that is, into those laid down in swamps or in the neritic zone, etc. Instead they are divided into the Clastic Rocks made up of fragments of older rocks and the Non-Clastic Rocks, which are either composed of material of organic origin or were deposited as chemical precipitates.

The Clastic and Non-Clastic Sedimentary Rocks are then subdivided, as shown below, on a basis of their chemical and physical characters.

CLASSIFICATION OF THE SEDIMENTARY ROCKS

1. Clastic Rocks	Rudaceous Rocks	Boulders and pebbles
	Arenaceous Rocks	Sands
	Argillaceous Rocks	Clays
2. Non-Clastic Rocks	Calcareous Rocks	Limestone, etc.
	Evaporite Deposits	Gypsum, Rock Salt, etc.
	Ferriferous Rocks	Iron Ores
	Siliceous Deposits	Flint and Chert
	Phosphatic Deposits	—
	Carbonaceous Rocks	Peat, Lignite, Coal, Oil accumulations

It must be clearly realized that the dividing lines between these groups are entirely arbitrary and that each group includes a large variety of rock-types, which grade into one another and into those of other groups. A typical limestone is easily distinguishable from a typical sandstone, but one sometimes finds a rock, consisting of

sand grains in a calcareous ground-mass; a rock that can be described with equal accuracy as a sandy limestone or a calcareous sandstone. In the succeeding account only the characteristic members of each group are dealt with. They are rock-types which are widely distributed both in time and space but during field work one often finds rocks that show a combination of the features given here as distinctive of separate groups. This is not surprising for the areas in which 'typical' rocks were deposited must grade into each other and it is in such places that the transition types were formed.

Rudaceous Rocks

Except for certain pyroclasts, these are the coarsest grained of all rocks. They may contain boulders up to several tons in weight, and were laid down either on a land surface or in very shallow water. If the material is unconsolidated it is described as a boulder or pebble bed or a gravel, according to the average size of its constituents. The shape of fragments, whether rounded or angular, will depend on the amount of abrasion which they have suffered, and on their hardness. A boulder bed composed of angular material will usually be *polygenetic*, i.e. will contain different kinds of rocks derived from several sources, for the material has not travelled far enough for the softer fragments to have been broken up. A storm beach, on the other hand, is usually *monogenetic* in character, i.e. the pebbles are all of the same tough rock-type and are usually extremely well rounded, owing to the vigorous battering against each other they have suffered.

Water percolating through an unconsolidated bed may deposit certain of the compounds held by it in solution to form a *matrix* or cement binding the fragments together. If the fragments are angular, the resultant rock is called a *breccia*, if they are rounded a *conglomerate*, whilst if some of the fragments are rounded and others are angular, the term *breccio-conglomerate* is used. The strength of the rock depends mainly on the nature of the cement. The well-known Hertfordshire Puddingstone, consisting of flint pebbles in a siliceous matrix, breaks with smooth faces, for pebbles and matrix are of equal hardness, both being composed of silica. But more often the matrix of breccias and conglomerates is either ferruginous or calcareous and then the rock breaks along uneven surfaces, for the pebbles are harder than the matrix.

Diagenesis, or the lithification of sediments, is caused not only by cementation, but also by compaction due to the pressure of overlying material and of earth movements. Cementation is more effective in

the porous rudaceous and arenaceous deposits, compaction in finer-grained, and therefore less porous, sediments.

Arenaceous Rocks

The arenaceous or sandy deposits are made up of grains between 2 mm. and 0·1 mm. in diameter. They are formed in a variety of environments, as desert or coastal dunes, on flood-plains, on beaches or further offshore in the shallow waters of seas or lakes. The conditions of deposition determine whether a sand is well-graded, i.e. the grains are all about the same size or ill-graded with much variation in size. Well-graded sands are due to either wind action or prolonged sorting by moving water. The grains are usually well rounded, particularly in the case of millet seed sands. In an ill-graded sand, however, the proportion of angular grains is usually much higher, and the sand is usually 'sharp' to the touch.

The grading of a sand can be determined either by passing it through sieves of varying aperture and then weighing the amount retained on each sieve or by elutriation, which is the reverse process to sedimentation. A current of water is passed upwards through the sand so that all grains below a certain diameter are carried away. By regulating the velocity of the current it is possible to wash off successive fractions of definite grain size and so carry out a *mechanical analysis* of the sediment. Elutriation is considerably slower than sieving, but is more accurate, especially if the sand is ill-graded and contains much material of the clay and silt grades. The results of either sieving or elutriation are usually plotted as cumulative percentages (Fig. XIII, 1).

Sands are usually composed almost entirely of quartz grains, which can withstand a great deal of attrition. Quartz has a specific gravity of 2·65 and if an ordinary sand is placed in a vessel containing a heavy liquid like bromoform with a specific gravity of 2·80, the quartz grains will float, whilst any heavier grains will sink and can be collected. The proportion of heavy minerals is usually less than 1 per cent of the total weight of the sand, but they are of considerable importance. Certain minerals are found in igneous, others in metamorphic rocks, so that the heavy mineral suite of a sand may give useful evidence as to the nature of the rocks from which it was derived. Samples taken at intervals along its outcrop may also indicate the direction of provenance of the material, the grains being larger, less abraded and more numerous towards the source of supply. It has also proved possible, at certain horizons, to use heavy minerals for correlating beds; for if scattered outcrops of sand all yield the

same suite of minerals, especially if some of the rarer minerals are consistently present, one is justified in regarding these outcrops as part of a bed laid down contemporaneously in the same basin of deposition. The study of heavy minerals and of their distribution has

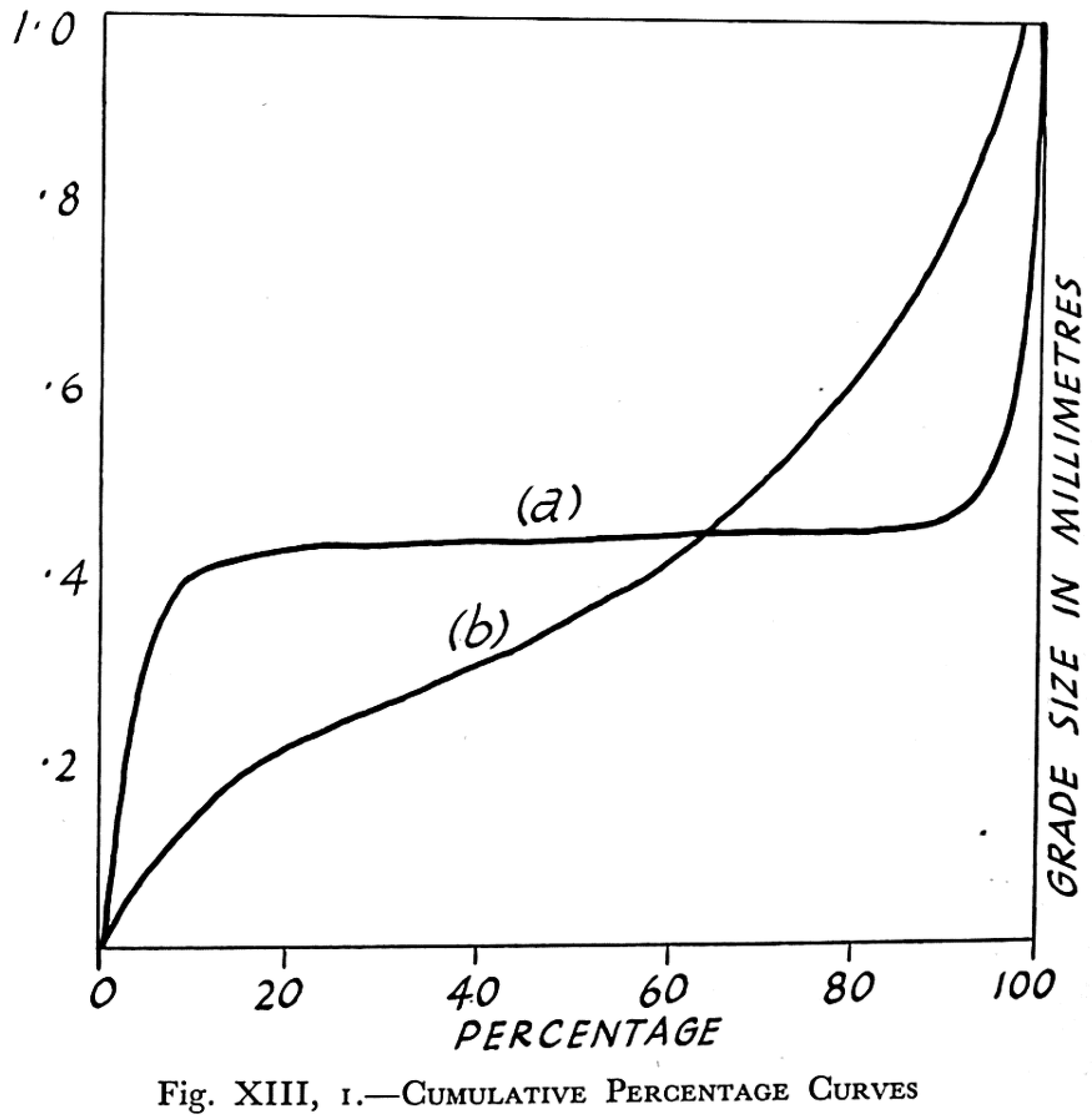


Fig. XIII, 1.—Cumulative Percentage Curves

(a) A well-graded glass sand.
(b) A poorly graded sand suitable for concrete work.

therefore become an important branch of Sedimentary Petrology, but it is one that cannot be taken further in this book.

Sands and gravels sometimes contain concentrations of rare minerals, usually those of very high specific gravity like gold, silver, platinum and tinstone. Such *placer deposits* are normally found in the flood-plain and terrace gravels (Fig. X, 9) of regions of considerable relief, where the rocks have been deeply weathered. The native gold, native silver, native platinum and tinstone are not affected by the

chemical weathering and, as the weathered material is being carried downstream, the heaviest materials are deposited as natural concentrations, wherever the current slackens, as for example on the inside of meanders or below rapids.

Gold placers of this type occur in Alaska, California and Australia. The gold is usually in the form of minute flakes, which are found by panning, that is, by placing a handful of sand and gravel in a shallow iron pan with water and then giving the pan a gentle circular motion, so that the lighter particles are swept over the side and the heaviest grains remain. Sometimes the native gold is found as large masses or nuggets, such as the Welcome Stranger nugget, weighing 141 lb. found at Ballarat in Australia. The rich tin-bearing gravels of Malaya are worked by washing the gravels through settling trays, in which the tinstone is trapped, whilst the lighter material passes on.

Placer deposits sometimes contain diamonds, as in the river gravels of the Gold Coast, Brazil and elsewhere, whilst in the Namaqualand fields the diamonds are found in raised beach deposits. Other placer deposits, for example those of Brazil, contain a high concentration of the rare earth minerals (compounds of zirconium, cerium, yttrium, etc.) or as in Ceylon, gemstones such as rubies, sapphires and garnets.

But such occurrences are extremely rare. Sands are normally composed almost entirely of quartz, with small amounts of iron oxides and hydroxides coating some of the grains and colouring the beds various shades of brown, yellow or red. The economic uses of such sands depends both on their grading and on their chemical composition. For building purposes the sand must be 'sharp', i.e. ill-graded with numerous angular grains, which will interlock. Chemical composition is less important, provided that the sand has not been in contact with salt water, which will sweat sooner or later in the building. Glass sands, on the other hand, must have a very high silica content with negligible amounts of iron, as otherwise coloured glass will be produced. Grading is rather less important, but a well-graded sand will melt more uniformly in the furnace. Moulding sands should contain appreciable quantities of iron oxides, to act as a bond to hold the grains in position in the mould. For concrete work, it is essential that the coarse aggregates are composed of pebbles of the same hardness. The river and terrace gravels and sands of the lower Thames form excellent aggregates, for they are composed almost exclusively of flint, but the gravels from the upper Thames around Oxford are much less suitable, for they consist of

a mixture of tough flint and soft limestone pebbles. The mechanical composition of the fine aggregates is important for it is essential that unnecessary amounts of cement should not be used and also that spaces between the larger pebbles should be completely filled with the fine aggregates, for 'voids' reduce the strength of the concrete (Fig. XIII, 1).

Sands, like gravel and boulder beds, are often converted into sandstone by cementation or to a lesser extent by compaction. It is usual to preface the word sandstone by an adjective stating the nature of the cement, i.e. ferruginous or calcareous sandstone; other types such as a cupriferous sandstone being much more uncommon. A sandstone with a siliceous cement is referred to as a quartzite.

In addition there are a number of special types of sandstone:

Greensands contain appreciable quantities of glauconite (p. 192).

Micaceous sandstones have many flakes of mica lying along the bedding planes and are often termed flagstones, owing to the ease with which they can be split along the bedding.

Ganisters are sandstones with a very low content of alkalis and, because of this absence of fluxing material, they can withstand very high temperatures and are used for furnace lining.

Arkoses are sandstones containing appreciable amounts of feldspar. They are formed from rocks that have suffered mechanical but not severe chemical weathering, by which the feldspars would have been decomposed.

Greywackes are very ill-graded sandstones, with a considerable amount of clay in the matrix. They are the products of rapid transportation and deposition, so that the material has escaped much sorting.

Grits are coarse-grained sandstones, often with scattered pebbles, and feel rough to the touch.

The main use of sandstones, apart from special types such as ganisters, is as building stone (*see* Chapter XIX).

Silts are composed of particles with a diameter between 0·1 and 0·05 mm. Both in silts and in their indurated form, siltstone, the individual particles are just visible with a good hand lens. The pores between the silt grains are so minute that the high surface tension prevents the free movement of water and as a result silts, though composed of the same material (quartz) as sands, have many of the physical properties of clays, especially lack of cohesive strength and relative imperviousness. They are very liable to cause trouble in engineering works of all kinds.

ARGILLACEOUS ROCKS

The clays are composed of the finest clastic material, usually less than 0·05 mm. in diameter. The breakdown of rocks by chemical weathering produces a group of silicates known as the Clay Minerals. Owing to their minute size these minerals are very difficult to investigate and much work remains to be done on them.

The clay minerals settle very slowly through moving water, so apart from areas of heavy flocculation such as estuaries, they are normally deposited in the quieter parts of rivers, in sheltered lagoons and lakes or beyond the 'mud line' at the edge of the continental shelf. Owing to their generally flattened shape, clay particles are transported very easily by wind and are blown far away from the areas of sand-dune formation.

When clays are deposited they usually have a very high content of water. Induration of the clays, whether by the weight of overlying sediments or by earth movements, squeezes out a great deal of this contained water and presses the particles into contact, causing the growth of larger, though still very minute, grains.

Clay as it is indurated becomes *claystone* and then, if it is fissile or with closely spaced bedding planes, the claystone passes into *shale*, or if it is not fissile into *mudstone*. More intense pressure due to tectonic causes will change either the shale or mudstone into slate, but this is a true metamorphic rock (*see* p. 174).

The main types of clay rocks are:

Varve Clays consisting of regular alternations of clay and silt layers. They were formed in glacial lakes, the silt layer being the coarser material carried down by the floods of spring and early summer, the clay material settling more slowly during the remainder of the year. The rhythmic banding is therefore seasonal with each pair of layers representing the deposit of one year. The annual layers are usually very thin, a millimetre or so, but thicker ones, due to exceptional weather conditions, occur at intervals and can be used as 'marker horizons' in correlating the varve clays exposed at different localities. By counting the varve clay layers exposed in sections in Sweden and by using marker horizons for correlation, it has been possible to show that the whole of Sweden was covered by ice only 15,000 years ago and that the ice retreated a distance of 450 miles towards the Norwegian mountains in about 5000 years.

Loess is a pale yellow or buff deposit of silt and clay, which covers great areas in central Asia and southern Russia and is less widespread in Germany and northern France. It is an aeolian deposit, formed towards the end of the last Ice Age, when strong winds were sweeping

across the vast spreads of material, with a high content of rock flour left behind by the retreating ice-sheets. Loess is normally unstratified but it has strong vertical partings, due to the roots of the grasses which flourished on the steppes. As a result, the roads and rivers, worn into the soft loess, have vertical walls. The 'limon' of France and the 'adobe' of the western United States are of similar origin.

Marine Clays are usually blue or bluish-grey in colour weathering, when the contained iron is oxidized in the zone of weathering to shades of brown. Clays that were deposited near the 'mud line' are usually uniform in character over wide areas. These clays, when uplifted, often contain numerous fossils, for the sea floor was well oxygenated and conditions were favourable for life. But in sheltered seas like the Black Sea or some of the Norwegian fjords with a barrier preventing the outflow of bottom waters, conditions become very unsuitable for life. Black muds are deposited, foetid with undecomposed organic matter owing to lack of oxygen, and smelling of hydrogen sulphide. Unfossiliferous black shales containing considerable amounts of iron pyrites were probably laid down under such *Euxinic* conditions.

The *Red Clay* of the deepest parts of the oceans has already been described (p. 111).

Marls are clays with a high content of calcium carbonate.

Boulder clay (*see* p. 69) is a transitional type between the rudaceous and the argillaceous rocks, for it consists of glacial erratics, sometimes of great size, set on a clay matrix. When lithified it forms a very rough rock, known as *tillite.*

The chief economic uses of the clay rocks are for brickmaking and the manufacture of cement. Bricks are made by thoroughly mixing clay or shale with water and then forcing the 'pug' through a rectangular aperture and cutting it into blocks. The green bricks are then fired in a kiln at a temperature of about 1750°F. A chain of large brickworks extends along the outcrop of one clay, the Oxford Clay, from Peterborough past Bedford towards Oxford. This particular clay is unusually carbonaceous and therefore contains much of the fuel needed to fire the bricks. As a result it is very economical to use but the bricks made from it have not the crushing strength of brick made by somewhat different methods from other clays.

For the manufacture of cement, the clay is mixed with the correct amount of crushed limestone and water to form a slurry. This is passed through great rotating steel kilns, sometimes over 100 yards in length. At the firing point, where the temperature is above 3000°F., clinker consisting of complex silicates of lime and alumina

is formed. The clinker, after it has cooled, is ground to extreme fineness.

Fire Clays are fossil soils like ganisters. The plants have removed all the alkalis, so bricks made of fire clay can withstand very high temperatures.

Pottery Clays have a high content of kaolin and are the result of the chemical weathering of granite.

Calcareous Rocks

The calcareous rocks are composed mainly of calcium carbonate, which forms a considerable part of the solution load of rivers but makes up only 0·01 per cent by weight of the total salts contained in sea water. This is due to two factors. Firstly great numbers of organisms make their skeletons of calcium carbonate and secondly, unlike most other chemical compounds, the solubility of calcium carbonate decreases with rise of temperature. Therefore when rivers flow into a hot, rather shallow sea, this acts as a natural evaporating basin and chemical precipitation occurs with calcium carbonate the first salt to come out of solution. Limestone is relatively soft and easily abraded, so that calcareous deposits of clastic origin, i.e. limestone conglomerates, are uncommon.

Calcareous Deposits of Organic Origin

These are to be found either in the oozes of the ocean depths (*see* p. 110) or in deposits laid down in shallow water.

In shallow water, limestones of organic origin are formed wherever lime-secreting organisms flourish in sufficient numbers. Coral reefs are an obvious case, but organic limestones have been formed by many other groups of organisms, including crinoids (p. 240), brachiopods (p. 240), and the lime-secreting algae (p. 247). Even in lakes and ponds snails may be sufficiently numerous to give rise to richly calcareous marls or to rather soft and earthy limestone.

Limestones of Chemical Origin

In limestone regions, the water percolating through the fissures of the rocks is saturated with calcium carbonate. If this water reaches the air, it will evaporate and precipitate the dissolved lime. If evaporation takes place at the roof of a cave, a hanging *stalactite* will be formed. If the water contains iron or copper salts, as well as the lime, the stalactites and stalagmites (rising from the floor) will be beautifully coloured. Precipitation also occurs round springs in limestone regions, *tufa*, a light-coloured porous rock, being formed.

In the so-called petrifying springs, precipitation is so rapid that any object placed in the water soon becomes coated with lime, and appears to have been turned into stone. Tufa also forms inside caves, in places where the dripping of water is too rapid to form distinct stalactites and stalagmites. The solubility of calcium carbonate increases with rise of pressure and therefore precipitation is particularly rapid round springs coming from a considerable depth and *travertine*, or calc-sinter, more compact and more banded than tufa, is formed. Travertine from Italy is a popular decorative stone, for it can be easily hewn at the quarry but after exposure to the air it hardens sufficiently to be cut and polished to show the intricate arrangement of dark and light layers.

Chemical precipitation also takes place in shallow warm seas, in which the surface waters are oversaturated with lime, whilst the sea is not so deep that the excess lime precipitated is dissolved before it reaches the sea floor. Precipitation of lime under these conditions is often aided by the presence of lime-secreting bacteria. Limestones formed in such an environment often show an *oolitic* structure, being composed of tiny spheres, looking like the roes of fish. If an oolitic limestone is examined under the microscope it is seen that each oolith (or sphere) consists of concentric layers, usually crossed by radiating cracks. A fragment of shell or a sand grain often forms the centre of an oolith or of the larger more ellipsoidal bodies known as pisoliths. Ooliths are being formed today in the Bahamas and off the Florida coasts, where tidal currents are washing sand grains, shell fragments, etc., backwards and forwards across chemically precipitated calcareous ooze and so by a 'snowball' action the ooliths grow until they are too big to be moved. Crystallization of the ooze will produce limestone composed of ooliths set in a mosaic of calcite.

The oolitic limestones of the Cotswold Hills and the Isle of Portland range from pure white even-textured oolites like the Bath and Portland building stones to shelly oolites containing many fossils, usually rather broken, whilst in other types many of the ooliths are composed not of calcium carbonate but of iron compounds. These ferruginous oolites, which are usually brown in colour, merge into the sedimentary iron ores (p. 191).

If the sea floor on which precipitation occurred was not disturbed by currents the calcareous ooze consolidated into a very even-textured rather greyish limestone, sometimes known as a 'chinastone', but *calcite mudstone* is a more accurate name.

The calcium carbonate of calcareous rocks occurs either in the form of calcite or of aragonite. Certain classes of organism secrete

shells of aragonite, others of calcite, whilst the conditions of chemical precipitation determine which mineral is deposited. Aragonite is much less stable than calcite and during consolidation of the rock any aragonite present is very apt to change into calcite but in the process the structure of the rock is altered. Corals, crinoids and brachiopods all secrete shells of calcite and therefore have a good chance of preservation but the aragonite shells of other bivalves and univalves may be obliterated, so that a fossiliferous limestone may now contain only a portion of the forms of life which lived on the sea floor.

Dolomitic Limestones

An important group of the carbonate rocks are those which contain magnesium carbonate as well as calcium carbonate. The two carbonates may form a dolomitic rock, composed of the mineral dolomite $MgCO_3$, $CaCO_3$, but more often crystals of dolomite occur in a matrix of calcite or *vice versa*, producing a dolomitic limestone. Weathered surfaces of such dolomitic limestones often present a a fantastic appearance, as in the Cannon Ball Limestone of Sunderland, which consists of spheres of calcite from which the less resistant dolomite matrix has been weathered away.

Dolomitic limestones may be either of primary or secondary origin. The primary types were formed in sheltered lagoons in which the two carbonates were precipitated together, but in the secondary types, an originally calcareous rock has been altered sometime after deposition by the percolation of magnesium-charged solutions. Such subsequent dolomitization is often seen to be selective; calcite fossils being preserved in a dolomite matrix, showing that an aragonite mud has been altered but that the fossils had been too resistant.

Uses of Limestones

One important economic use of the calcareous rocks in cement manufacture has already been mentioned. Cement may be made by taking pure limestone and mixing it with clay. Certain clayey limestones are, however, natural cement mixtures for they contain clay and calcium carbonate in the necessary proportions. Examples of the use of both types of raw material can be seen near London. Near Gravesend, river mud is mixed with the pure limestone of the Upper Chalk, whilst around Maidstone the quarries work the marly beds at the base of the Chalk.

Limestone is used very extensively in blast and other furnaces as a flux to facilitate melting of the charge, and it is also used on a

considerable scale as a top dressing for roads (p. 291). Considerable quantities of crushed limestone are sold as 'agricultural lime' and are spread on fields and gardens to reduce the acidity of the soil. In a later chapter we shall refer to some of the many good building and decorative stones formed by various types of limestone.

Evaporite Deposits

Sea water contains dissolved salts, the average proportions of which in parts by weight per 1000 parts of sea water are:

Sodium chloride ($NaCl$)	27·2
Magnesium chloride ($MgCl_2$)	3·8
Magnesium sulphate ($MgSO_4$)	1·7
Calcium sulphate ($CaSO_4$)	1·3
Potassium sulphate (K_2SO_4)	0·9
Magnesium bromides	0·1
Calcium carbonate ($CaCO_3$)	0·1
Total about	35

If sea water is evaporated to dryness it is found that these salts are precipitated in the following order:

1. $CaCO_3$
2. $CaSO_4$
3. $NaCl$
4. Mg salts
5. K salts

so that the complete evaporation of a body of sea water would produce a sequence of deposits showing the following stratigraphical succession:

4. Polyhalite layer (K_2SO_4, $MgSO_4$, $2CaSO_4$, $2H_2O$)
3. Rock Salt layer ($NaCl$)
2. Anhydrite layer ($CaSO_4$)
1. Limestone or Dolomite

Evaporite deposits often show this sequence but their thickness needs explanation, for the complete evaporation of 1000 feet of sea water would produce a total thickness of less than 15 feet of salt deposits and of this less than 1 inch would consist of anhydrite, and yet in some areas beds of anhydrite many feet in thickness are to be found.

Thick evaporite deposits therefore can only form in basins into which a constant supply of salt-laden water is moving to replace that

which is precipitated. A good example is given by the Gulf of Kara Bughaz, a shallow lagoon on the eastern side of the Caspian Sea.

Evaporation in the Gulf is so rapid that a powerful current flows into it from the Caspian Sea, bringing in about 350,000 tons of fresh salts each day. The table below, in parts of salts per 1000 of water, shows how concentrated are the waters of the Gulf:

	Caspian Sea	Gulf of Kara Bughaz
$NaCl$	8	83
$MgCl_2$	0·6	129
KCl	0·1	10
$MgSO_4$	3	62
Total about	12	284

Gypsum is deposited in vast quantities, but rock salt still remains in solution, for the waters of the Gulf are not sufficiently concentrated for sodium chloride to be precipitated.

The Dead Sea is another example of a natural evaporating basin. In this case the River Jordan flows over rocks containing beds of fossil salt so that the solution load of its waters is already high before they enter the Dead Sea. The waters of the Dead Sea are so brackish and buoyant that people bathing find it difficult to sink below the surface and have to wash afterwards in fresh water to remove the encrusted salt.

Evaporite deposits can also form in temporary or playa lakes such as Lake Eyre in the Australian desert. This 'Lake' is usually a vast salt-encrusted plain, towards which rivers drain but they dwindle and finally disappear before reaching it. In 1949 and 1950, however, there were exceptionally heavy rains both over the 'Lake' and on the surrounding hills. The rivers flooded and by July 1950 a real lake roughly equal in size to Norfolk and Suffolk combined, and in places more than 12 feet in depth, had been formed. Since then the rains have reverted to normal and successive expeditions have watched the shrinking of the lake, for the rapid evaporation caused the level to fall by 115 inches between October 1950 and December 1951, whilst salinity increased from twice to seven times that of normal sea water. The increasingly brackish nature of the water killed off the fish, which lay stranded round the shrinking lake. The lake finally dried up completely but fresh deposits of salt and gypsum have been added to the material on its floor. In the course of time a considerable thickness of evaporite deposits can be formed by the repeated flooding and drying up of such playa lakes.

The potassium-bearing salt deposits, very important economically, are much less common than are thick beds of rock salt or gypsum for the potash salts being extremely soluble are the last to be precipitated. They will only be preserved if, immediately after precipitation, they are sealed from subsequent solution by a layer of impervious material. In the famous Stassfurt deposits in northern Germany the potash salts occur beneath a layer of clay, fossil loess, and a similar relation holds in the recently discovered deeply buried potash field in north-east Yorkshire.

But not all salt deposits are interbedded with other sediments. In some areas, notably in north Germany, Texas and Iran, there are numerous *salt domes* (Fig. XIV, 3) piercing their way through bedded rocks, which are usually domed up and strongly faulted round the plug. In Iran, in an area of very low rainfall, these plugs form hills down the sides of which are flowing slow-moving glaciers of salt, carrying as erratics rocks brought up from very considerable depths. In Germany and Texas the formation of the salt domes ceased long ago and most of them are hidden beneath an unconformable cover of younger rocks. The mode of formation of such domes is uncertain. Salt, like ice, can flow slowly by the sliding of crystals over each other but the problem is whether the salt produced the domes by forcing its way upwards or whether the domes were formed by earth movements and the salt then moved into these areas of lower pressure. The general view is that uprising salt is unlikely to have been the motive force in producing such domes.

Evaporite deposits do not show the relative horizontal uniformity of other sedimentary rocks. They were precipitated in isolated basins and, as shown by the analyses below in parts of salts per 1000 of water, the composition of the water of different basins varies considerably, depending on the nature of the surrounding rocks:

	Dead Sea	Great Salt Lake, Utah
$NaCl$	64	119
$MgCl_2$	164	15
$CaSO_4$	1	1
Na_2SO_4	–	9
Total	229	144

The actual salts precipitated will depend partly on the evaporation history and partly on complex chemical reactions, whilst finally there may be considerable post-depositional changes due to percolating water.

In arid regions surface efflorescences sometimes occur, owing to the evaporation of mineral-charged solutions rising up through porous sands or gravel. In the nitrate fields of western Chile, the 'caliche' consists of a mixture of potassium and sodium nitrates with small quantities of calcium and magnesium nitrate. These nitrates were possibly derived from the weathering of volcanic rocks in the Andes and were carried in solution through the sands and gravels of the outwash fans at the foot of the mountains and then, owing to the intense evaporation in the desert belt, were precipitated as efflorescences.

FERRIFEROUS ROCKS

By chemical weathering the iron-bearing minerals are broken down and, under suitable conditions, the iron is transported by rivers as part of their solution and suspension loads. On reaching the seas flocculation may take place and then the iron compounds are precipitated, usually in the form of either the carbonate, siderite, or the silicate, chamosite.

Precipitation often occurred in shallow sheltered lagoons, into which relatively little terrigenous material was being carried; conditions rather similar to those in which oolitic limestones were formed and, indeed, the oolitic limestones of the Cotswolds pass northwards into the oolitic iron ores of Northamptonshire. These ores consist mainly of ooliths of chamosite in a matrix of sideritic mud, but other varieties occur, including the 'iron shot' oolites, composed of ooliths of limonite in a calcareous matrix. These ores were considerably affected by diagenetic changes and in the zone of weathering, chamosite and siderite are altered into limonitic crusts, often in the form of boxstones. At other localities, as around Cardiff in South Wales and in the Clinton field of the Appalachians in the United States, the iron was precipitated in the form of the ferric oxide, haematite.

The bedded oolitic iron ores of the English Midlands consist of continuous seams, with an iron content greater than 30 per cent. They can be worked open-cast by the largest mechanical excavators. But in the long abandoned iron field of the Weald and in some of the coal fields, iron ore occurs as lines of ellipsoidal concretions of sideritic clay-ironstone, often oxidized externally to limonite, set in shale. These ores are not of marine origin but were formed in swamps, where the abundant decomposing vegetation helped the precipitation of the iron compounds carried by the rivers. These ores, even the 'Blackband Ores', consisting of alternate layers of coaly and

ferruginous material, are not worked today, despite as high an iron content as the Midland ores, for it is uneconomic to move the great quantities of shale, etc., that have to be shifted to extract small nodules scattered along the bedding planes.

In the swamps of Sweden, Finland and Canada, sediments are being deposited containing a high proportion of limonite, often of concretionary habit and associated with manganese. Bacterial action seems to have played an important part in the precipitation of these bog iron ores. The quality of the ore is poor, for it is usually highly phosphatic and contains much clastic and organic material.

In Sussex near Midhurst, and in Dorset around Abbotsbury, are strongly limonitic deposits, which have not been worked as iron ore, for they are too siliceous to be smelted easily. These deposits seem to have been formed by the contemporaneous oxidation of glauconite on the sea floor. Glauconite is a complex silicate of potassium and ferric iron, which occurs in arenaceous deposits as scattered grains. It is particularly abundant in the 'greensands', though as it is very easily oxidized to limonite, weathered greensands are any shade of brown or red and it is only the unweathered greensand that is really greenish-hued. Greensand and glauconitic muds are being formed today in many places along the edge of the continental shelves and therefore the presence of unrolled grains of glauconite in unfossiliferous deposit is regarded as evidence of marine origin. As glauconite is only forming in places where sedimentation is very slow, we can go further and regard glauconite as an index not only of marine conditions but also of slow deposition—a view supported by the other features of glauconitic rocks.

Despite this, the precise conditions for the formation of glauconite are uncertain. The older view was that it could only form within the shells of foraminifera, which provided an enclosed space in which complex chemical changes could take place, but more recent work suggests that glauconite is formed by the breakdown, under special conditions, of micas or other ferro-magnesium minerals.

In Cumberland and in north Spain occur important deposits of haematitic ores, often with an iron content greater than 50 per cent; not bedded, but as irregular masses in limestones. The ore bodies are of metasomatic origin, that is, they were formed by aqueous solutions percolating through the consolidated sediment. Secondary dolomitization (p. 187) and secondary silification (p. 194) are other examples of metasomatism. The haematitic ore bodies are either in the form of inverted cones ('sops'), hundreds of yards in diameter and hundreds of feet in depth, or of narrow veins ('flats')

along the major joints and fault planes. The sops are clearly solution hollows in the limestone. The mineralizing solutions, which have attacked the limestone, may have been of deep-seated (hydrothermal) origin, but more probably percolated downwards from ferruginous sands, which used to overlie the limestone. Cavities were formed first and were later infilled with haematitic ore, which partly replaced the limestone of the cavity walls.

Iron content is not the only factor that determines whether a ferriferous rock is worked as an ore or not. Equally important are ease and cheapness of quarrying and smelting.

Siliceous Deposits

The rocks composed largely or entirely of clastic grains of quartz have already been considered under the Arenaceous Rocks. We are concerned here with those deposits which were of organic or chemical origin and in which the silica is often in the form of opal or chalcedony.

During weathering, silica passes into solution and it is estimated that nearly 12 per cent of the solution load of rivers consists of silica. But the silica content of the seas is extremely small, for sponges (p. 238), diatoms (p. 236), and radiolaria (p. 238) abstract it to form their skeletons, whilst silica can also be precipitated, under conditions which are not yet fully understood.

Whilst discussing deep sea deposits (p. 110) reference was made to the siliceous oozes. Radiolaria are entirely marine, but diatoms can live in both fresh or salt water. If the diatoms flourish abundantly and if there is little detrital material, diatomaceous earths may be formed on lake bottoms, as in some of the Scottish lochs. Diatomaceous earth or kieselguhr is used as an abrasive and, being chemically inert, as a filler for a variety of purposes including the manufacture of explosives.

Whilst some sponges live in fresh water, the majority are marine. Locally the 'glass' sponges, with a siliceous skeleton, form colonies or sponge banks. Silica is also deposited locally around hot springs, as siliceous sinter or geyserite.

Far more abundant than the types of siliceous deposits described above are flint, chert and silicified limestone. Along the bedding planes of limestones and certain sandstones, irregularly shaped nodules of extremely fine-grained siliceous material are often found. Those occurring in the Chalk are known as *flint*. They are usually black internally and break with a conchoidal fracture, whilst the *chert* nodules found in other rocks are often brown-hued and break

with an even fracture. But the two types flint and chert really grade into one another and one can find nodules of chert which are indistinguishable from the familiar flint nodules of the Chalk. It is therefore more reasonable to regard flint as a special variety of chert; a variety which is restricted to the Chalk.

The origin of chert (including flint) is still uncertain. One view is that it is of *syngenetic* origin (contemporaneous with the enclosing sediment), the nodules having been either deposited chemically as silica gels or laid down organically as sponge debris which has undergone a certain amount of solution and redisposition. This is possible, for organically deposited silica is opaline and is fairly easily soluble in alkaline waters. But normally flints and chert contains few recognizable traces of sponges and, therefore, a direct organic origin is unlikely. Another possibility is that they were formed penecontemporaneously by alkaline solutions moving through the sediment, whilst it was still unconsolidated, dissolving the scattered remains of radiolaria, diatoms and sponges and then precipitating the silica round some nucleus. A third theory is that the nodules are *epigenetic* (subsequent) in origin and that they have been formed by precipitation from percolating solutions after the consolidation of the rocks.

It is very probable that there is no one explanation for the development of chert (including flint). Certainly one finds isolated cases that seem to have been formed in one or other of the ways suggested above but far more often the mode of origin is debatable.

The tabular sheets of flint and chert, sometimes found infilling joint- or fault-planes and inclined at a high angle to the bedding, are clearly of syngenetic origin, for the fissures along which the silica-charged waters have moved could not have opened until after the consolidation of the beds.

Cherts grade into the silicified limestones, which usually retain traces of their original oolitic, dolomitic or organic structures. Such silicification is often selective. The silicified limestones of the Pennines are frequently 'rottenstones', consisting of hollow spaces once occupied by fossils in a fine-grained siliceous matrix. The calcareous ooze has been silicified but not the calcite shells of the fossils. Subsequently percolating acidic water has dissolved away all trace of the shells, but has not affected the silicified matrix. Similarly in the Chalk one finds sea urchins (p. 240) preserved in flint but usually all traces of the very thin shell have gone and one is left with a silicified impression or cast of the ooze, which had filtered into the shell after the decay of the soft parts of the organism.

Man's first tools were made of flint. At Grime's Graves in

Norfolk and at Cissbury Hill in Sussex are some of the mines from which he obtained the flint. The chief use of flint today is in concrete aggregates. Flint and chert are too brittle to make high quality road stones, whilst as building stones they require more skill in dressing and laying than is usually available today.

Phosphatic Deposits

Apatite, a mineral widely distributed though only in small quantities in igneous rocks, is the ultimate source of the phosphatic deposits. On weathering, apatite breaks down into soluble compounds, which are absorbed by plants and to a greater degree by animals, the phosphorus being particularly concentrated in teeth and bones. Phosphorus is returned to circulation on the death of the organism or from its excreta.

Phosphatic deposits are being formed today as the 'guano' which caps certain tropical islands, produced by the droppings and skeletons of myriads of sea birds. As the phosphates are soluble such concentrations can only occur on semi-desert islands. In Algeria and parts of the Rocky Mountains there are extensive deposits consisting of phosphate-rich layers interbedded with argillaceous rocks, which are of marine origin. At one time it was held that these beds had been formed by the catastrophic destruction of vast numbers of organisms but it seems more reasonable that they were deposited in part as precipitates, under conditions which prevented normal organic decay and hence the release of phosphatic material. Pieces of shiny black phosphate, in the process of formation, have been dredged from the sea floor off southern California, always from places in which deposition seems to be taking place extremely slowly.

At intervals in the stratified rocks are to be found beds of phosphatic nodules consisting of clay, sand or small pebbles cemented together by calcium phosphate and often partly enclosing, or sometimes completely enveloping, fossils. The nodules are usually hard and black and show evidence of exposure for long periods on the sea floor, for they are rounded and are often covered with oysters or bored by organisms. Such nodule beds yield a mixture of fossils, which normally occur in a considerable thickness of strata. They must have been formed by the erosion of bedded phosphatic deposits, followed by a concentration of the nodules. At still other horizons *bone beds* occur. These consist of coprolites (fossilized excreta) and the teeth, bones and scales of fish, often encrusted by secondary phosphate. Such bone beds must have been formed in areas of strong current action, for the amount of fine-grained material is very small.

All this evidence shows that phosphatic nodule beds and bone beds are *condensed deposits* of small thickness but representing a considerable period of time. They were formed in areas strongly scoured by currents under conditions similar to those in which glauconite forms, and indeed phosphatic nodules are often glauconitic or are found in glauconitic deposits.

The phosphatic nodules and bones used to be separated by hand-picking from the other pebbles and then crushed to form fertilizers. But with the development of chemical methods of manufacturing phosphates the nodule beds became uneconomic to work, though guano and the bedded phosphatic deposits are still profitable.

Carbonaceous Rocks

The Carbonaceous rocks are dominantly of organic origin. They can be divided into two groups, which grade into one another. In the *humic* group, including peat, lignite, house coal and anthracite, the organic matter is of a woody nature; but the *sapropelic* group, comprising cannel coal, oil shales and the source rocks for natural oil and gas, were derived mainly from the more resinous parts of plants or from the oil-secreting algae.

The sapropelic coals are mainly composed of material which was transported or drifted to the place of accumulation, but the humic coals were formed in situ at the place where the vegetation grew. This is proved by the wide extent of individual coal seams, which are underlain by a fire clay or ganister, a fossil soil containing the roots of plants; whilst the shale or sandstone, forming the roof of the seams, indicates a marked change in conditions, usually the flooding of the swamps in which the plants grew, by either fresh or salt water. In most coalfields the seams of humic coal comprise only a very small percentage of the total thickness of rocks. A rhythm of the type shown in Fig. XIII, 2, is repeated time and time again, showing that periods of plant growth were separated by long periods when clastic rocks were being deposited. The present thickness of the rock-types gives no clue as to the relative duration of the episodes of organic and clastic accumulation, for the coals have been much compacted by the load of later rocks. It is probable that the peat was compressed to about a fifteenth of its original thickness during its conversion to coal, so that a seam of coal of workable thickness, that is, three feet or more, represents a fifty-foot thickness of peat.

Such thick accumulations of carbonaceous material can only occur in areas where the breakdown of plant tissues by bacterial action is retarded. This may be due to such rapid growth that the

lower layers are quickly carried below the level of bacterial action or accumulation may take place in too cold water or in stagnant water, in which the concentration of certain products of decomposition becomes great enough to kill off the bacteria gradually. Considerable thicknesses of peat are forming today in Alaska, Labrador and elsewhere in high latitudes and also beneath the luxuriant vegetation of the coastal swamps of the southern United

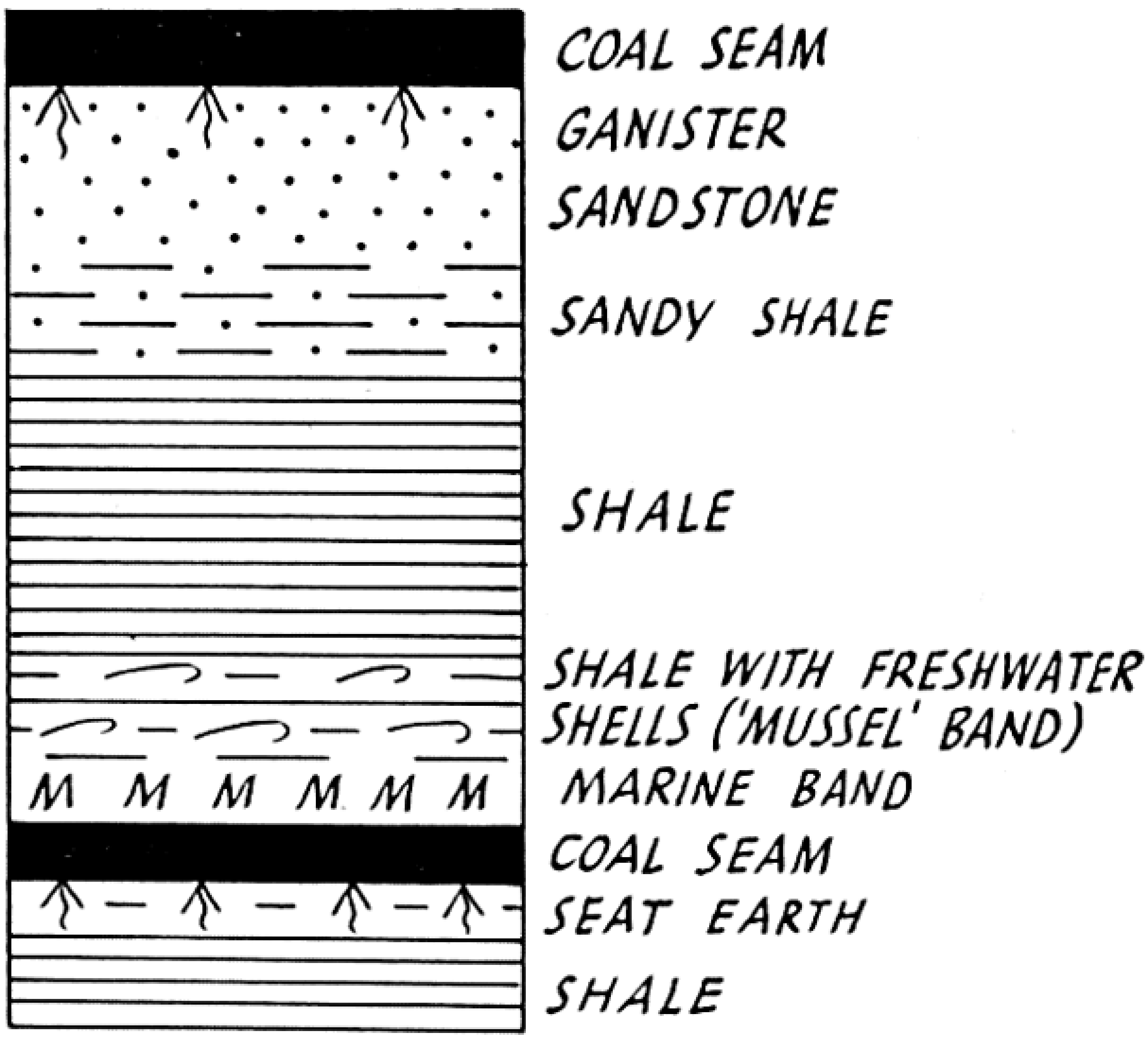


Fig. XIII, 2.—Rhythmic Sedimentation in the Coal Measures

This kind of rhythm is repeated time and time again. The thickness of shale is usually considerably greater than shown here, the coal often forming only a few per cent of the total thickness of rocks in each rhythm unit.

States. During certain periods of the past similar swamps were developed much more extensively. About 250,000,000 years ago, during the later part of the Carboniferous Period, a great belt of swamps extended from north to south across the British Isles and eastwards across northern France, Belgium and northern Germany to the borders of Russia. The peat which formed in these swamps has been changed by the passage of time and the pressure of the later sediments into seams of humic coal. As a result of earth movements followed by great erosion, the coal is only found today in synclinal basins or coalfields for it had long ago been removed from the intervening anticlinal areas (*see* Fig. XVIII, 3).

The chemical changes undergone by vegetable matter as it is changed from wood through peat and lignite to coal and finally anthracite are shown below:

	Carbon	Hydrogen	Nitrogen	Oxygen
Wood	50	6	1	43
Peat	55	6	2	37
Lignite	73	5	1	21
Bituminous Coal	84	6	1	9
Anthracite	93	3	1	3

These are average values, expressed as percentages by weight of dried material. There is also a gradual change in physical characters—an increase in density and a gradual disappearance of obvious organic structures. In lignite or brown coal, fragments of wood, bark and leaves are easily recognizable but they have disappeared in the bituminous coals. The bituminous coals are, however, not of uniform structure like anthracite but are composed of numerous layers, formed by one of the following substances:

Fusain, a charcoal-like material, which smears the fingers. Under a lens a distinct cellular structure may be visible.

Vitrain, forming the lustrous bright layers, which are clean to the touch, but are brittle, breaking with a conchoidal fracture.

Durain, the dull, earthy looking layers, contrasting markedly with the lustrous vitrain. They consist of spore cases and other very resistant parts of plants.

Clarain, very thin alternations of bright and dull laminae with a smooth fracture and a silky lustre. The bright layers are composed of woody tissue, the dull ones of plant debris which has lost all trace of original structure.

The humic coals can also be arranged in the following series of increasing 'Rank':

	Percentage content of volatile matter	*Calorific value in B.T.U.s*
Peat	75–50	Less than 10,000
Lignite	55–45	11,000–12,000
Sub-Bituminous Coal	50–40	12,000–14,000
Bituminous Coal	about 40	14,000
Semi-Bituminous Coal	more than 20	14,000–15,000
Semi-Anthracites	20–10	15,000
Anthracites	less than 5	15,000

This is a continuous series, with increase in rank meaning a reduction in volatiles, an increase in the carbon content and, at first, an improvement in calorific value, though the coals of the highest

rank (the anthracites) may be of lower calorific value than certain semi-bituminous coals. This is compensated for, however, by a change in other properties, as for example a lower ash content.

Lignites are found in the Tertiary and Mesozoic rocks, the bituminous coals in the Palaeozoic strata. Rank is therefore to some extent related to the age of the coal and probably also to the weight of over-lying sediments. According to the views put forward by Hilt and often referred to as 'Hilt's Law',

(i) in a single coalfield, the more deeply buried coals are of the highest rank;

(ii) the rank of a seam increases, if it is traceable into a strongly folded area, or into the vicinity of igneous rocks.

There are numerous examples of the last generalization. The lignite seams of the Canadian Plains change into bituminous coals, when traced into the folded strata of the Rocky Mountains, and, both in the South Wales and the Appalachian coalfields, bituminous coals become anthracitic in the zones of strongest folding. Seams are altered by dykes and sills into, first, a narrow belt of anthracite and then, at the contact, worthless graphite cinder. But the first generalization is not generally accepted. It is possible that for the coals of lower rank, differences in the original composition of the peat, or the amount of bacterial decay before the peat was covered by other sediment, may have been more important in determining rank than the post-depositional effects of load metamorphism.

Many coals, particularly the bituminous coals, are affected by a closely spaced jointing or 'cleat', which is usually persistent in direction through any one field.

The *cannel coals* occur as lenticles, not as continuous seams. They are massive, without the different layers of the humic coals and break with a conchoidal fracture. Their ash content is usually much higher than in the humic coals, as is the proportion of volatiles, so they can often be ignited with a match to burn with a smoky flame, hence their name cannel or candle coal. They have been formed in ponds on the coal swamps; ponds into which were washed the spores and more resinous parts of plants together with, often, a considerable amount of clastic material. The lenticles of cannel coal often contain the remains of water fleas and fish, which lived in the ponds.

The cannel coals grade on the one hand into the humic coals and on the other into the *boghead coals* or *torbanites*, which are dark in colour and, though tough, can easily be scratched with a knife. Under the microscope boghead coals are seen to contain great numbers of translucent yellow masses, which are the remains of oil-secreting

algae. Today in certain lakes, notably Lake Balkash in Turkestan, oil-secreting algae flourish in sufficient abundance, at certain seasons of the year, to cover the lake with a film, which accumulates on the shores as a rubbery-like substance. Oils, mainly of the paraffin series, are obtained by the distillation of boghead coals.

The bogheads, in their turn, grade into the *oil shales*, composed of argillaceous material, heavily impregnated with bitumen and, in addition, much finely divided plant debris and many minute spherical bodies that are believed to be of algal origin. The oil shales of the Edinburgh neighbourhood have long been worked, not so much for the petroleum and paraffin wax, which can be distilled from them, as for a by-product, ammonium sulphate. The quarries show well-bedded layers separated by thicknesses of 'curly' shale, strongly crumpled and with lustrous slickensided surfaces. The beds seem to have been deposited in shallow fresh water lagoons. Underwater slipping of the waterlogged oily muds produced the layers of 'curly' shales.

The natural or *mineral oils*, that is, the hydrocarbons of the petroleum series, seem to have originated from fine-grained marine sediments with a high organic content. If such beds were laid down under anaerobic conditions, that is, in an environment deficient in oxygen, the organic debris would not undergo the normal processes of decay, and by a complex chain of reactions might be converted into the petroliferous hydrocarbons. These changes must have taken place before the compaction of the strata, for oil is generally found not in the source rocks but in the more porous or fissured 'reservoir' rocks into which it was squeezed. The commoner types of structure in which the migrating oil is trapped are described in Chapter XIX.

The migrating oil may reach the surface to form seepages or may partially evaporate to leave deposits of the heavier and more viscous fractions, such as the asphalt slowly welling up into the Pitch Lake of Trinidad or the rubbery-like deposits of bituminous matter, which sometimes line joints in the limestones of the Pennines and prove that mineral oil once passed through these rocks.

SECTION D

The Composition and Origin of the Earth

CHAPTER XIV 23/4/83

Earthquakes and the Interior of the Earth

THE geologist is normally concerned with studying the rocks of the Earth's crust, which is only a few miles in thickness. The Earth has a radius of 6400 kilometres (4000 miles), and for information about the deeper parts of the Earth the geologist is largely dependent on the geophysicist who has developed instruments and techniques for measuring the variation with depth of various physical properties of the Earth.

The study of *Earthquakes* (a branch of Science known as *Seismology*) is the chief way in which such information can be obtained. Earth tremors are produced by the movement of rock masses relative to one another. The vibrations produced may be so slight that they can only be detected by delicate instruments or they may be strong enough to cause a major earthquake. A severe earthquake causes widespread destruction of buildings and may alter the surface of the ground, especially in mountainous districts, where great landslides may dam rivers with the additional danger of disastrous floods if the mounds of unconsolidated material should break. The high death roll in certain earthquakes (140,000 in Japan in 1933, 300,000 in India in 1737 and 100,000 in Messina in Italy in 1908) was partly due to the scattering of domestic fires setting fire to the wrecked buildings and as the water mains had been fractured by the shock, fighting the fires was as difficult as it was in the early days of the bombing attacks on London and other cities. Earthquakes also occur beneath the sea. These may be just as destructive, for great waves or *tsunamis* (to use their Japanese name) may sweep for thousands of miles across the oceans and when they break on flat coasts drown many people for they are powerful enough to carry small boats several hundred yards inland.

If, after an earthquake, reports of the shock felt and the damage caused are plotted on a map, *isoseismal* lines can be drawn enclosing those areas in which the shock was of the same intensity. The scale used, first suggested by the Italian Rossi-Ferrol, is based on easily observed things, just as is the Beaufort scale for the measurement of wind strength. For example a slight shock (Force III) is only felt by people at rest, that is, lying or sitting down, in a very severe shock (Force V) people are wakened and bells rung, whilst a disastrous shock (Force VIII) dislodges chimneys and after a very disastrous shock (Force XI) few buildings are left standing and the ground is fissured.

When the map is completed, the isoseismal lines usually form ellipses with their longer axes parallel to a known fault line. The *epicentre* or place of maximum intensity is at the centre of the ellipses. In a number of earthquakes there has been additional evidence that movement has taken place along a fault line. A new fault line scarp has appeared with the country on the one side displaced a few feet or yards relative to the other side (Fig. XIV, 1). In some cases fences have been offset along the line, greatly to the benefit of the lawyers engaged in the ensuing litigation to determine the new boundaries of properties.

More precise investigation of earthquakes, and particularly of the types of waves produced, requires a *seismograph*. There are many different types, but the basic principle is the same (Fig. XIV, 2). A pendulum is so adjusted that one part of it, at least, remains at rest, whilst one end oscillates under the earthquake shock. The amount of movement is suitably magnified and recorded (usually photographically) on a drum rotating at a known speed. The record or seismogram obtained after a severe shock shows several distinct groups of waves. The first waves felt, the Primary or P waves, are compressional waves vibrating like sound waves in the direction of propagation. After a brief quiet period come the Secondary or S waves, which are 'shake' waves, vibrating at right angles to the direction of propagation. These are followed by the L waves of the main shock, moving like the waves of the sea. The L waves are usually succeeded by a period of after shocks, sometimes continuing for days and often strong enough to interfere seriously with the rescue work.

The Position of the Epicentre

The P, S and L waves travel with different velocities and hence by knowing the time interval between the arrival of the P and the

S waves it is possible to calculate the distance of the epicentre from the instrument. It must lie on a circle of certain radius. If the same shock has been recorded by a number of widely separated seismographs, circles can be drawn round each instrument and the epicentre must be the intersection of these circles. It is by this method

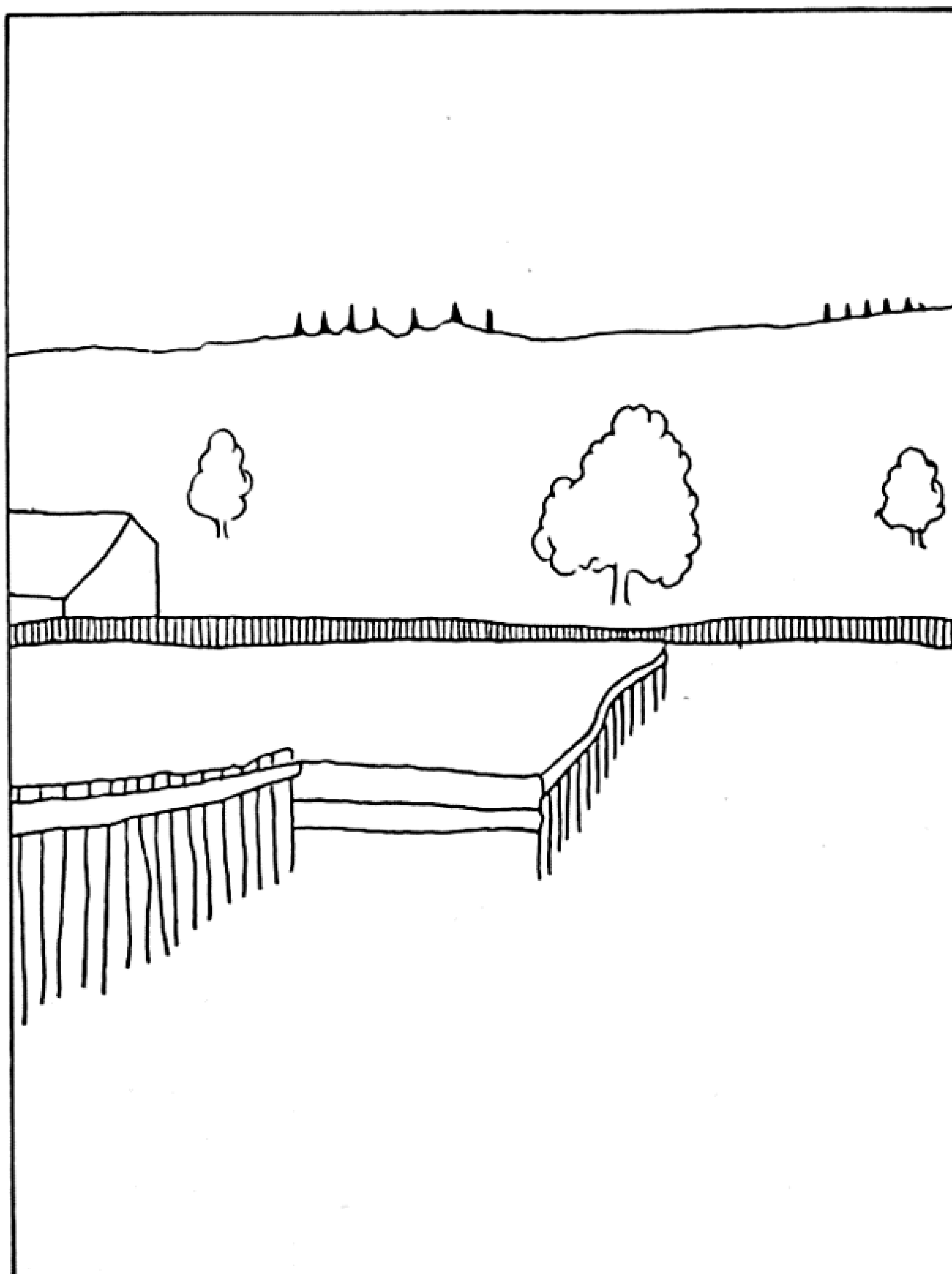


Fig. XIV, 1.—FENCE DISPLACED BY THE CALIFORNIAN EARTHQUAKE OF 1906 (DRAWN FROM A PHOTOGRAPH)

that the position of the epicentres of earthquakes occurring on the ocean floors is determined.

Earthquakes do not occur haphazardly anywhere in the World, but as shown by Fig. XIV, 3, nearly 90 per cent of the known earthquakes have been located either in the circum-Pacific belt or in the zone extending eastwards from the Mediterranean to the Himalayas. It is in the same regions that the most severe shocks have been felt.

In the remaining areas, earthquakes are much less frequent and usually very slight. The worst shocks recorded in the British Isles have usually only reached Force V (chimney pots dislodged), whilst the last known death due to an earthquake was as long ago as 1580.

By careful examination of the seismograms it is also possible to

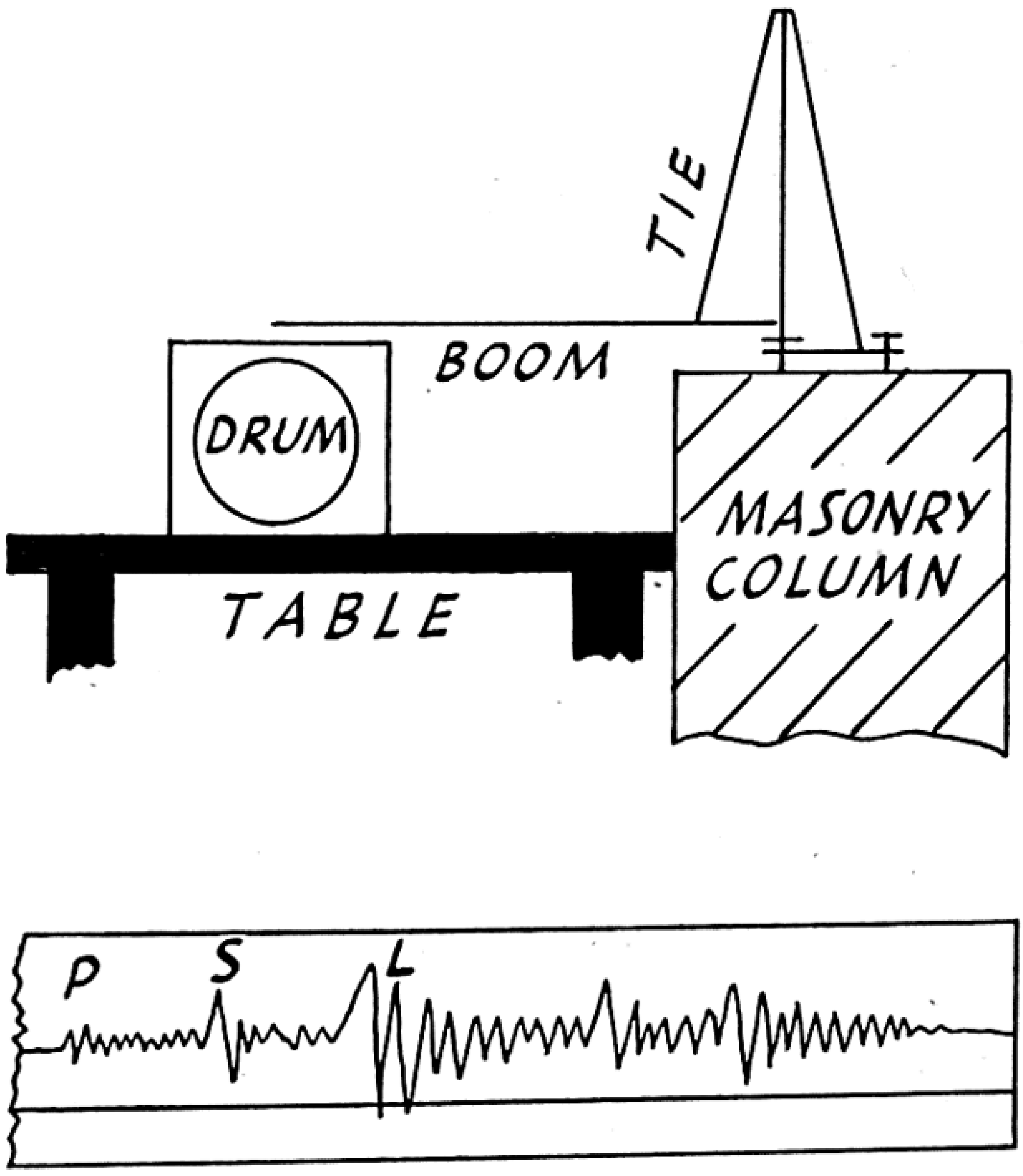


Fig. XIV, 2.—Seismograph (*above*) and Seismogram (*below*)
The movement of the tip of the boom is recorded photographically on the rotating drum.

calculate the depth of the place of origin or *focus* of the earthquake, lying directly below the epicentre. Whilst the great majority of earthquakes are of shallow-focus, 50 km. or less, deep-focus shocks may originate at depths as great as 750 km. These deep-focus shocks especially repay study, for whilst the L waves travel through the rocks of the crust, the P and S waves take a more direct path from the focus to the seismograph and therefore penetrate deep beneath the crust. The velocity of any wave is dependent on the physical properties of the material through which it passes and hence the analysis

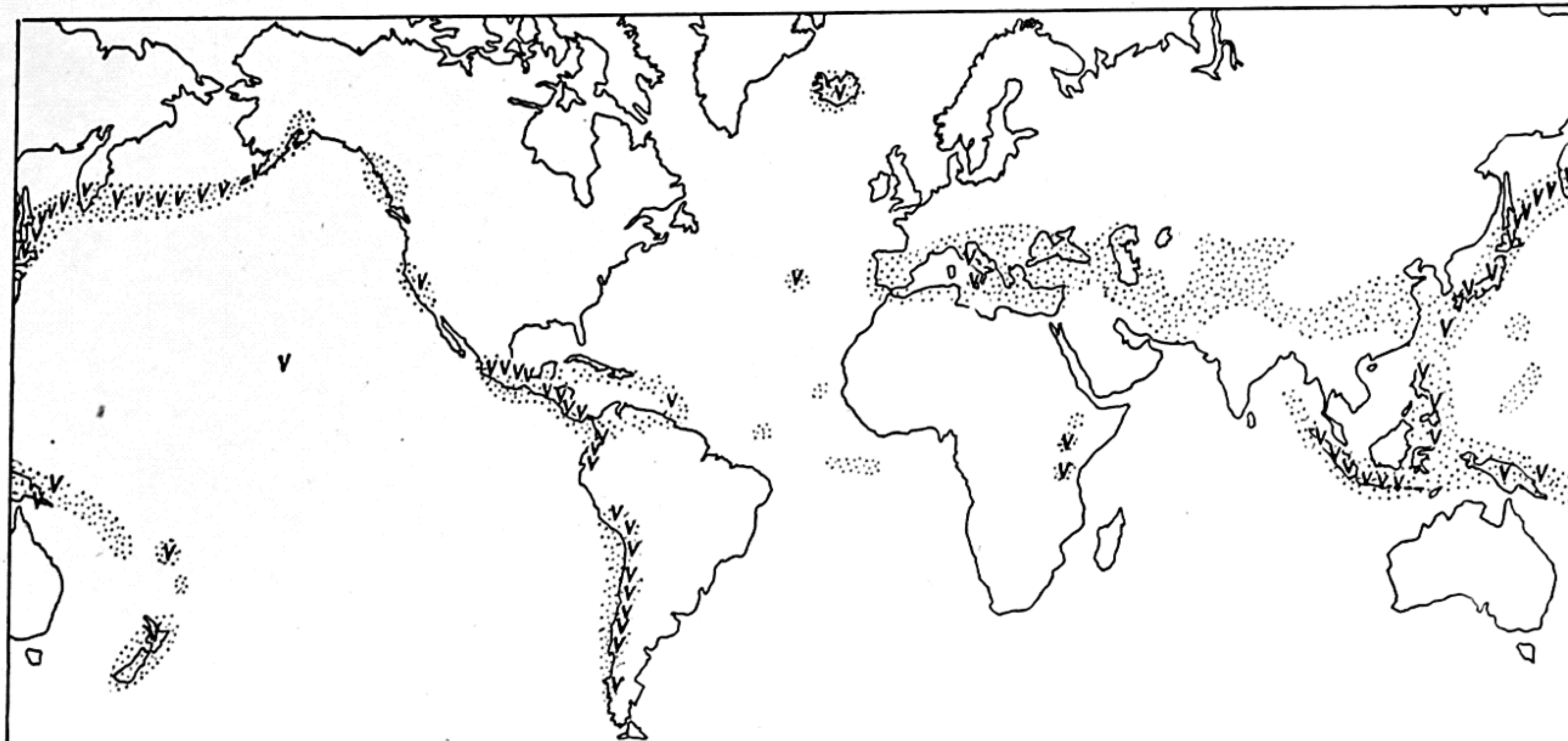


Fig. XIV, 3.—Areas of Maximum Earthquake Activity (Dotted) and the Main Centres of Recent Vulcanicity (V)

of distant earthquakes give us much information as to the nature of the material composing the interior of the Earth.

The Core of the Earth

The presence of a core or nucleus is shown by the fact that P, S and L waves are all received by seismographs up to a distance of about 11,000 km. (that is, 103° in angular measurement) from the epicentre. But between 103° and 143° from the epicentre there is a 'shadow zone' in which only the L waves are received, whilst from 143° to the antipodes of the epicentre, P and L, but not S waves, are recorded (Fig. XIV, 4).

This must mean that P and S waves penetrating to depths greater than 2900 km. reach a core, which does not transmit the S waves, whilst comparison of the time of arrival of the P waves at angular distances less than 103° and greater than 143° from the epicentre, shows that passage through the core has considerably reduced the velocity of the P waves. The radius of the core, slightly greater than half that of the Earth, is determined by the path followed by the 'grazing ray', the last to show P, S and L waves. The fact that the distortional S waves are not transmitted by the core suggests that it is composed of matter in the liquid or potentially liquid state, whilst the composition of the core is indicated partly by the velocity of the P waves (9 km. per sec.) through it. Additional evidence is given by measurements of the density of the Earth, which is 5·5 that of water and nearly twice that of the rocks forming the crust. The Earth must therefore have a core of high density, estimated to be 9·9 at the outside increasing, owing to the enormous pressures, to at least 12·2 at the centre. The 'nickel-iron' meteorites which fall at intervals on the Earth's surface are believed to be fragments of planetary material similar to that from which the Earth originated and closely resembling the material forming the Earth's core. These converging lines of evidence suggest that the core of the Earth is composed of iron with smaller amounts of nickel.

Density Stratification

The 'grazing rays' passing just outside the core travel at considerably greater velocities, the P waves at about 13·5 and the S waves at about 7·3 km. per sec., and from this it is concluded that there must be a sharp fall of density from 9·9 to 5·5 in the material surrounding the core. The velocity of the P and S waves decreases towards the surface, until in the shallowest waves travelling just beneath the surface, the velocities have fallen to 5·6 and 3·3 km. per

sec. respectively. But this decrease is not regular; for a number of surfaces of discontinuity have been detected at which there are marked changes in the nature and physical properties of the material

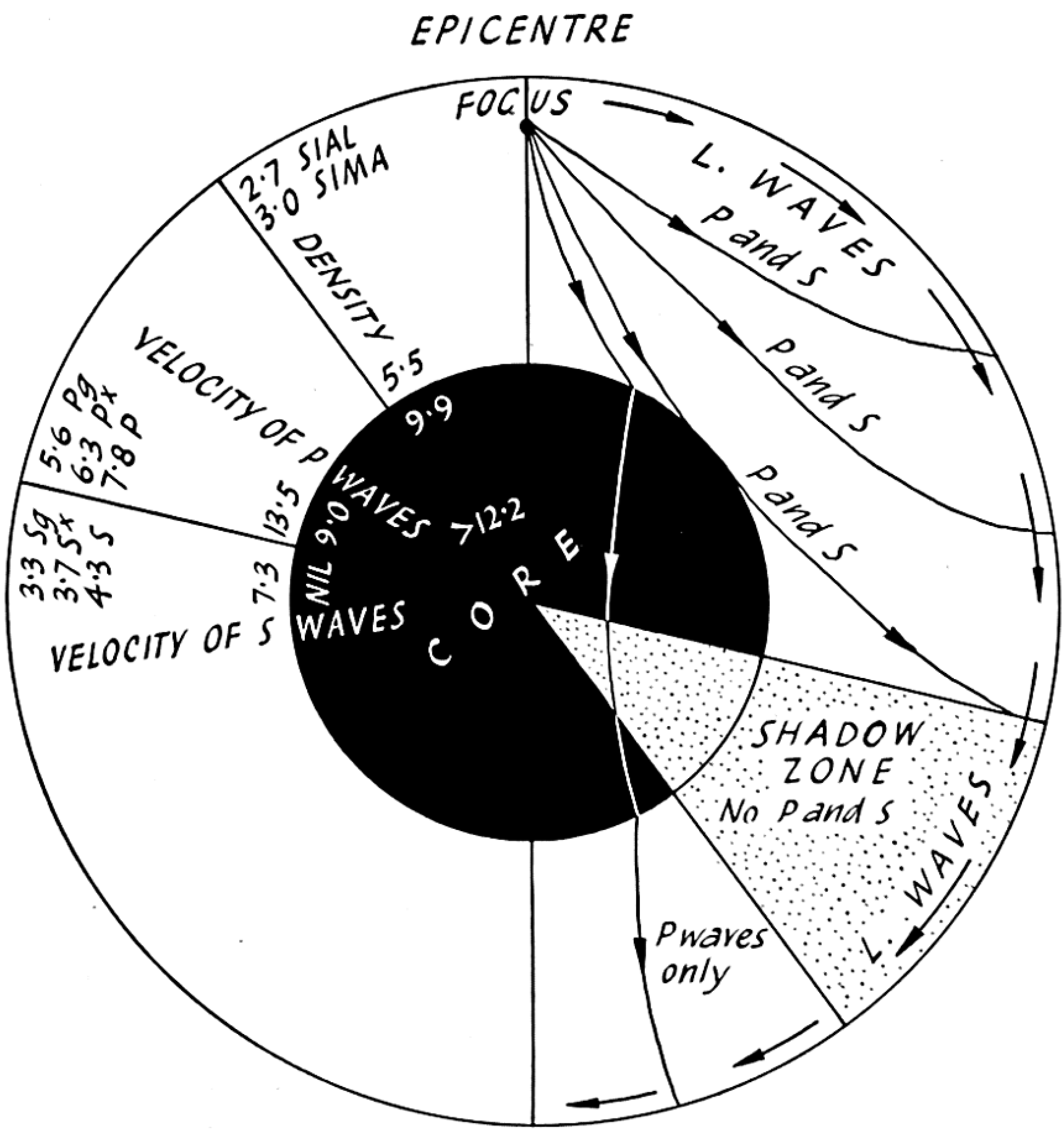


Fig. XIV, 4.—Interior of the Earth, Based on Seismological Data

On right: Paths followed by the different waves from a deep focus earthquake.

On left: Variation with depth of the velocity in km./sec. of earthquake waves and of the inferred density of rock material.

transmitting the waves. Whilst all seismologists agree that the core is surrounded by a number of layers, whose density increases with depth, there is disagreement as to the number and thickness of the individual layers. This need not concern us here, the essential point

being that the Earth shows a well marked density stratification with the densest material at the centre.

The Outermost Layers

The analysis of records of near earthquakes has shown that both the P and the S waves can be divided into three separate groups (Fig. XIV, 4), travelling at different velocities and following different paths. The velocity of the slowest and most direct waves (Pg and Sg) corresponds with that obtained by the experimental transmission of waves through granite. The faster Px and P waves have penetrated to greater depths to travel through material of higher density than granite before being refracted back to the surface. The composition of these deeper layers is not quite certain, but it is probable that the

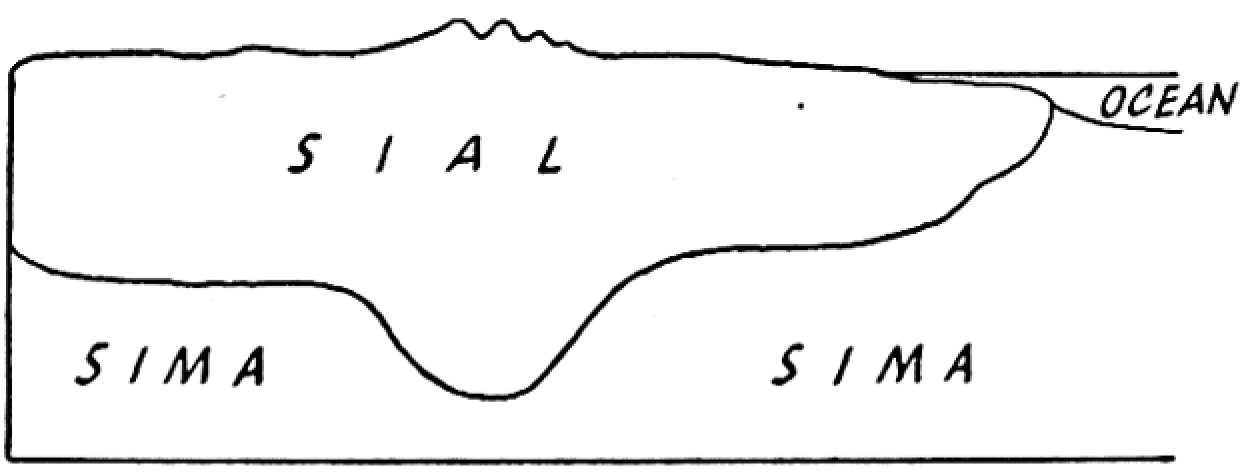


Fig. XIV, 5.—The Concept of Isostasy

A continental block of Sial (density 2·7) underlain by Sima (density 3·0 or above). Note the deep root beneath the mountain chain and the Sima forming the floor of the ocean basin.

granitic layer rests on material of basaltic composition, which may be in the form of tachylyte (basaltic glass) and this on still denser ultrabasic material of eclogitic (p. 175) composition.

The continents are therefore thought to consist of *Sial* (the composite name for sedimentary and granitic rocks, which are made up mainly of silica and alumina) resting on basaltic *Sima* (composed largely of silica and magnesia). The sialic layer is either absent or extremely thin on the floor of the ocean basins, so the sima of specific gravity 3·0 or greater is the outermost of the continuous shells that compose the Earth. It floors large areas of the oceans, particularly of the Pacific Ocean, but beneath the continents it is depressed to a depth of 30 km. or more and is overlain by sial with specific gravity about 2·7 (Fig. XIV, 5).

The Concept of Isostasy

Whilst the force of gravity everywhere attracts matter towards the centre of the Earth, it is possible to show with sufficiently delicate

instruments that both the force and the direction of the Earth's gravitational pull vary appreciably in different places. This variation is partly due to the attraction exerted by neighbouring masses of high land, such as a mountain range. If the volume of rock material above sea-level in the mountain range is known, it is possible to calculate the attraction exerted by this mass and therefore how much a plumb-bob should be deflected towards the mountains.

But during very accurate survey work in India in the middle of the last century, it was found that the deflection of the plumb-bob at a station near to the Himalayas was less than it should have been according to calculations of the attraction exerted by the mass of the Himalayas. The fact that the Himalayas did not attract the plumb-bob as much as expected could only be explained by supposing that their excess mass above sea-level was compensated for by some lack of material below sea-level.

From these observations was derived the Concept of Isostasy, according to which the areas of sial are 'floating' in a state of equilibrium on sima, so that there is a relation between the height of the different areas of the continents and of the mass of the column of rock underlying them. But there are two different views as to how this state of equilibrium is attained.

Archdeacon Pratt, trying in 1855 to explain the results of the Indian surveys, argued that the density of the material underlying a mountain range must be slightly less than that beneath a continental lowland and still less than that beneath an ocean basin. He thought that at what he termed the 'level of compensation', the downward thrust exerted by different blocks of the crust would be the same, the greater thickness of the less dense material underlying a mountain range being compensated for by the shorter but denser column beneath an ocean basin.

Sir George Airy, the Astronomer Royal, in the same year published a different opinion. He believed that there was no appreciable difference in the density of the material beneath different parts of a continent, but that instead of there being a 'level of compensation', the continents resembled icebergs floating in water, with a simple relation between the height of the ice projecting above water and the thickness of the ice below water. Airy pictured mountain ranges as underlain by a 'root' of sial penetrating deep into the sima (Fig. XIV, 5).

This analogy must not be taken too far, for the substratum of sima is solid not liquid, as it transmits S waves, but owing to the high temperatures at great depths, it must be weaker than the rocks

of the crust and capable of yielding slowly under long continued stress. This might be due to extra material being added to the surface of the continents, which would be depressed and then, when this material was removed, elastic recovery would cause isostatic uplift of the previously depressed areas. The development of continental ice-sheets is one way in which parts of the continents could be thus over-loaded.

A very fine series of raised beaches can be traced round the Baltic Sea. These beaches were formed by glacial lakes or shallow seas, during the final stages of the retreat of the ice-sheets of the last glaciation into the Scandinavian mountains. These strand lines must have been horizontal when they were formed, but now they are strongly warped. The highest and therefore the oldest, which can be traced at about present sea-level across extreme southern Sweden through Latvia and Esthonia to Leningrad, rises steadily as it is followed across Sweden and Finland, until around the head of the Gulf of Bothnia it is 900 feet above sea-level. Therefore this area, once the centre of the Scandinavian ice-sheet, must have been uplifted by this amount and indeed, the records of tide gauges and the slow recession of the tide-free Baltic Sea from prominent stones and quays shows that uplift is still proceeding in the Gulf of Bothnia at the rate of about 1 cm. per year (Fig. XIV, 6).

Raised beaches round the Great Lakes of North America show similar warping due to the *isostatic recovery* of the land from the weight of the ice-sheets, a recovery that has lagged appreciably behind the removal of the load.

Another cause of *isostatic* uplift may be the removal of material by erosion. It is much more difficult to demonstrate this by examples, but it has been suggested that the depth of the stupendous gorges cut by the River Brahmaputra as it flows southwards between Everest and Katchenjunga across the highest part of the Himalayas is due to the river having had to downcut most vigorously to maintain its path across a block that was being slowly isostatically uplifted.

In 1926 the Dutch geologist Vening Meinesz made a large number of determinations of gravity in a submarine on the floors of the seas around the East Indies. He found that in a narrow belt, only sixty or so miles in width but extending for nearly 4000 miles from a little south of the coasts of Sumatra to the south of Java to Timor and then swinging north-eastwards past the Celebes to the Philippines, there is a marked deficiency or 'negative anomaly' of gravity (Fig. XIV, 7). Later a similar narrow belt of negative anomalies was discovered in the West Indies. These belts of negative anomalies are

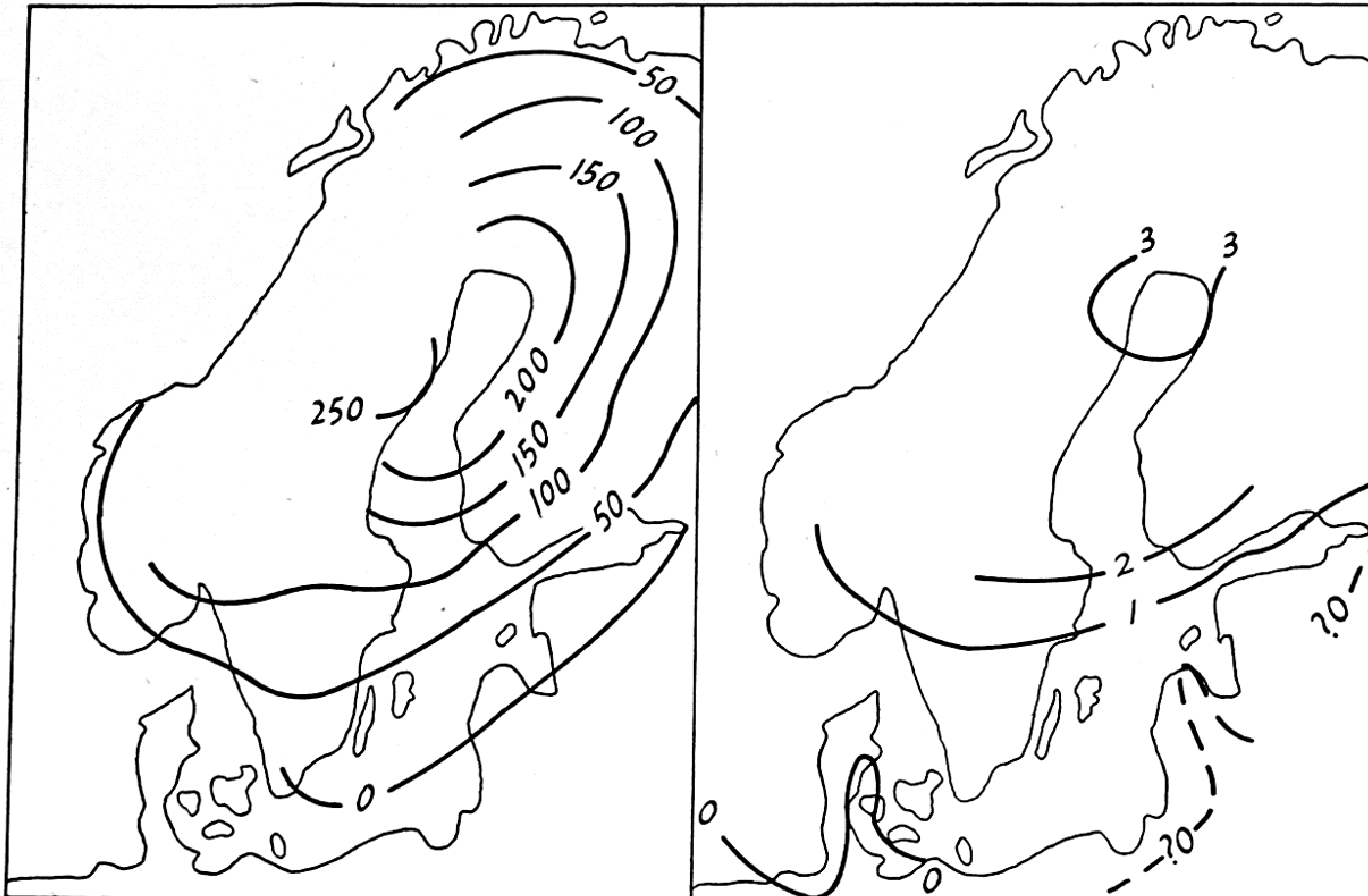


Fig. XIV, 6.—Isostatic Recovery of Scandinavia

Left: The present height in metres of the Rha Raised Beach cut about 9000 years ago (after Sauramo).
Right: Rate of uplift in feet per century at the present time (after Gutenburg).

believed to be underlain by deep roots, that is, by an unusually great thickness of material of relatively low density. The significance of this is discussed in the next chapter.

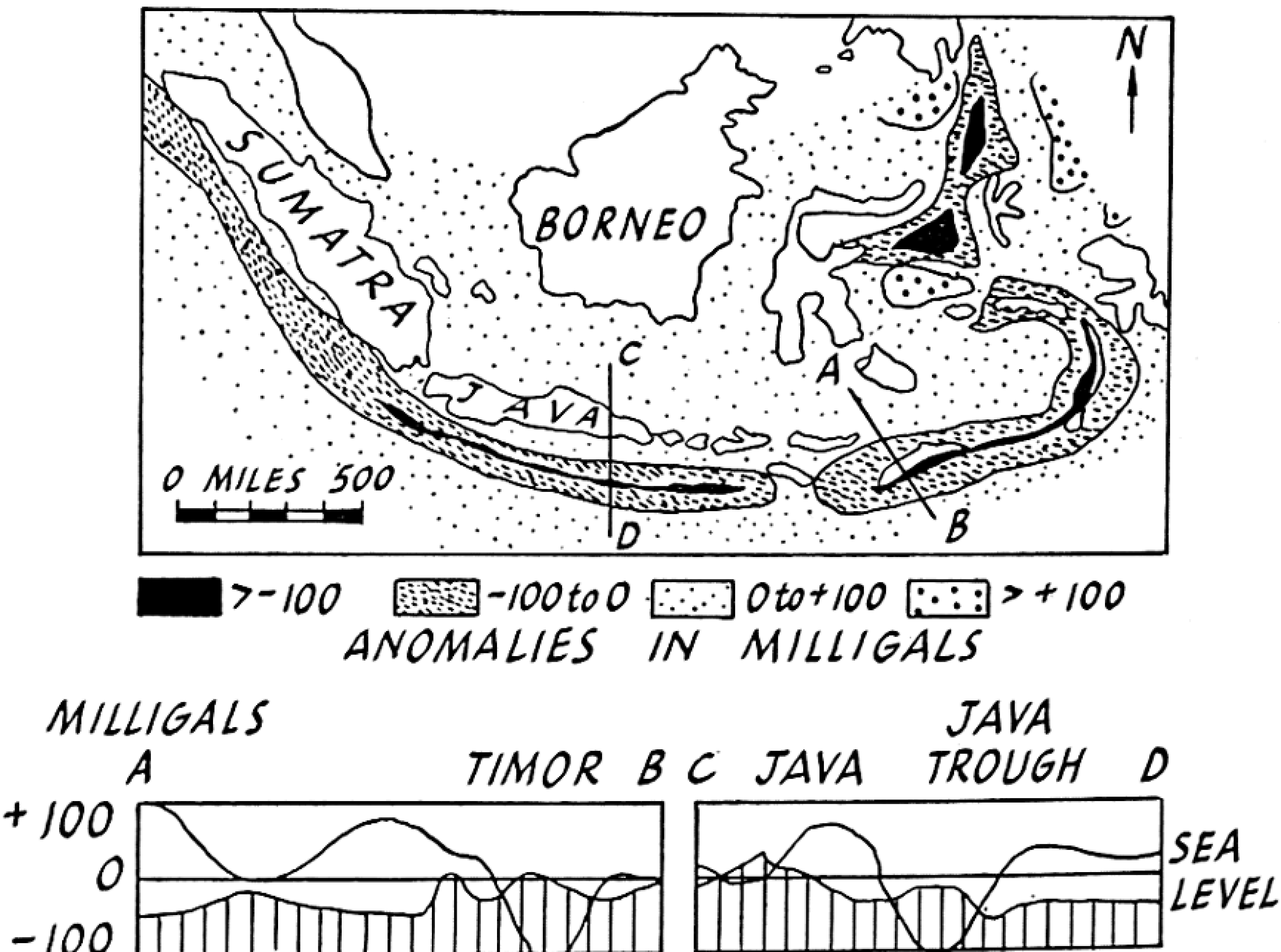


Fig. XIV, 7.—Map and Sections Showing Gravity Anomalies in the East Indies (after Vening Meinesz)

The Origin of the Earth

Whilst dealing with the Earth as a whole, we must refer to the question of its origin, though this unsolved problem is the concern of astrophysicists rather than of geologists. It is generally agreed that the Earth must have been formed as a separate body of the Solar System considerably more than 3000 million years ago. According to one theory a great star then passed sufficiently near to the Sun to set up tidal forces strong enough to cause the Sun to eject great filaments of matter, which coalesced to form the various planets of the Solar System. An alternative theory does not invoke such an exceptional event as the passage of a star of sufficient size at the necessary distance. The Solar System is regarded as having been derived from the condensation of a great disc or nebula of gaseous material spinning round the Sun. When the velocity of rotation reached a critical value, centrifugal force would throw off part of the

gaseous disc as a ring, which would relatively quickly coalesce to form a planet and then later another ring would be thrown off and so on. This Nebular hypothesis, originally suggested nearly 200 years ago by Kant and Laplace, was for a long time superseded by the Planetesimal hypothesis of Chamberlin, but within the last few years opinion has turned more in favour of re-examining the possibilities of the condensation of particles from a nebula.

However the Earth may have originated, it is probable that the solidification of the crust and the development of the atmosphere and of the oceans, took place fairly rapidly and that the stratified nature of the Earth as a whole dates from almost the commencement of its history.

CHAPTER XV

Orogenic Belts and Stable Blocks

THE British Isles can be divided fairly easily into areas in which two distinct groups of rocks outcrop (Fig. XV, 1). On the one hand are the regions where the rocks are strongly folded, metamorphosed and often injected by granitic and other igneous rocks. These contrast with the areas of unmetamorphosed sedimentary rocks; regions of simple geological structure with the folding of an open nature instead of overfolding and overthrusting. Igneous rocks are also usually absent except as dykes and sills or, in Antrim and western Scotland, as plateaux basalts. There is also a marked difference in topography, the metamorphosed areas being usually mountainous, the other areas lowlands diversified by scarps along the outcrop of the more resistant beds.

In other parts of the World a third major geological unit can be found. For example, in North America the flat-lying sedimentary rocks of the Interior Plains are bounded on either side by the steeply folded belts of the Rocky Mountains and the Appalachians but, to the north, the greater part of eastern Canada is a typical 'shield', being composed of intensely metamorphosed and very old rocks, injected by igneous masses and locally heavily mineralized. Topographically the Canadian Shield is monotonous: the intensely folded strata have been worn down to a peneplain, with a veneer of glacial deposits, laid down during the last Ice Age.

This marked difference in lithology, structure and topography of these three major units must reflect great differences in their history. Valuable evidence is given by a comparison of the sedimentary rocks of the lowland basins and of those parts of the mountain chains in which the folding has not been severe enough to destroy fossils and to obliterate the evidence of the environments in

which the sedimentary rocks were formed. Rocks yielding the same fossils and therefore of the same age will almost invariably be found to be many times thicker in the mountains than in the lowlands and

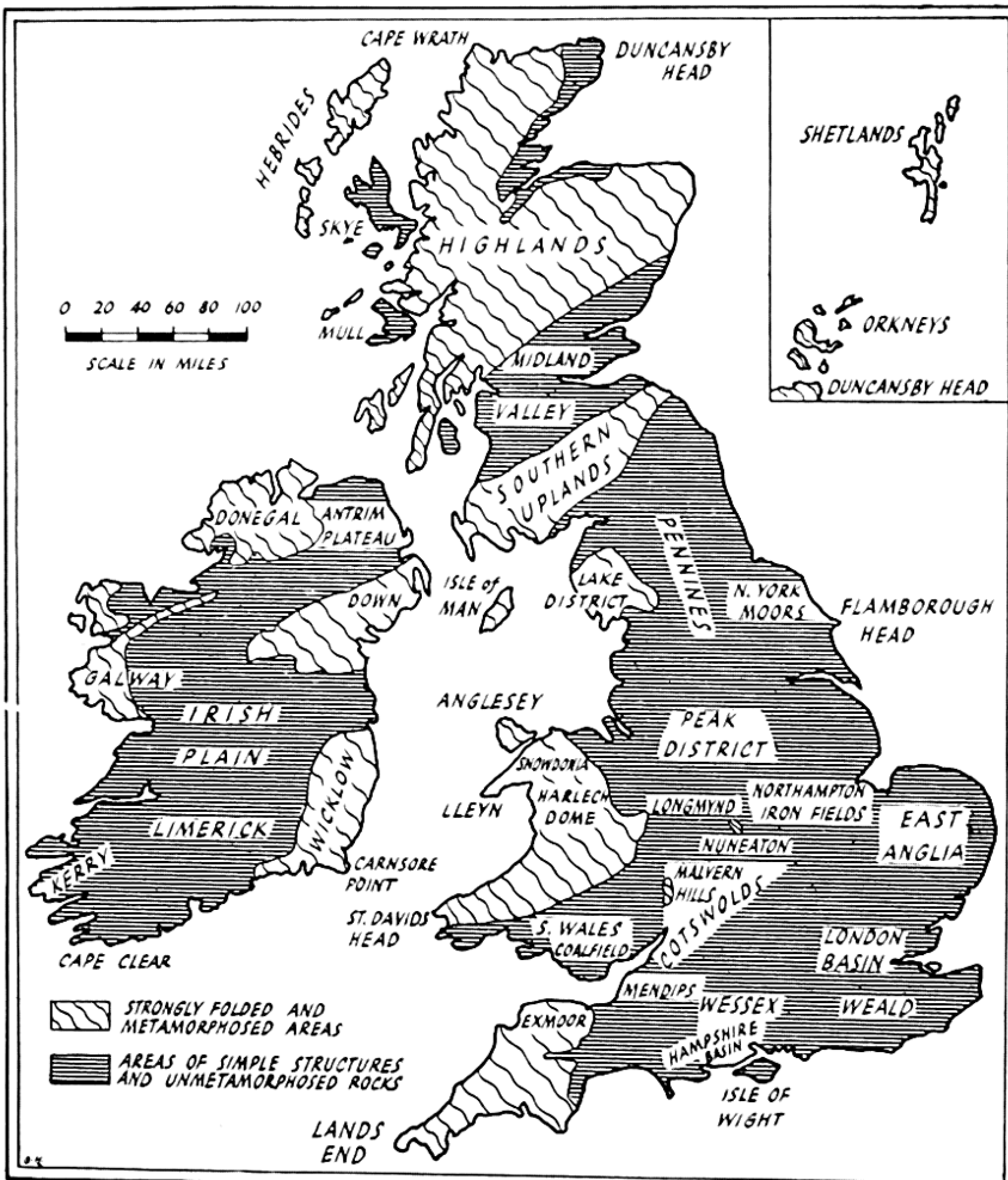


Fig. XV, 1.—Chief Geological Regions of the British Isles

also to have been deposited in fairly deep water, whilst those of the lowlands were formed in much shallower water or even on land.

It is therefore clear that the folded mountain chains of the World must have originated from long narrow seas, the floors of which subsided steadily to allow room for the deposition of a great pile,

several miles in thickness, of sedimentary rocks. Such depressed belts are known as *geosynclines*. They must have been bounded by more stable areas which were the source of the sedimentary material. After a prolonged period of deposition, with often at intervals brief episodes of volcanic activity, either in the form of pillow lavas or the building up of volcanic cones, which may have developed into volcanic islands, there followed a phase of Earth Movement or *Orogenesis*. The sides of the geosyncline moved towards each other, compressing and metamorphosing the great thickness of relatively weak sedimentary rocks, which were still further altered by the intrusion, from depth, of great masses of granitic and other igneous rocks. Then the whole metamorphosed mass was uplifted and carved by erosion into a mountain range.

The last great orogeny to affect Europe, the Alpine Orogeny, occurred about 35 million years ago. For the previous 200 or so million years great thicknesses of sediments had been accumulating in a geosyncline, the Tethys, extending from the Mediterranean regions of Europe eastwards through Asia Minor to the Himalayas. Deposition had been interrupted, at intervals, by volcanic outbursts and by a certain amount of folding, which must have produced lines of volcanic islands comparable to those of the developing East Indian geosyncline of today. The culmination of the orogeny occurred when the shield area of North Africa drove northwards towards the stable block of Europe. The rocks of the geosyncline were thrown into great recumbent folds or *nappes* separated by major thrust planes. The shortening of the crust in this region has been estimated to have been as much as 175 miles. The plan of the folds was controlled by resistant blocks such as the Massif Central of France and the Bohemian Massif (Fig. XV, 2).

The British Isles have been affected to varying extents (*see* Section E) by at least two other orogenies, the Armorican about 220 million years ago and the Caledonian about 320 million years ago, whilst the oldest rocks of the Highlands of Scotland, the Pre-Cambrian rocks, formed more than 500 million years ago, are believed to show evidence of, at least, two still older orogenic episodes. In the British Isles the Pre-Cambrian rocks are exposed in only small areas, being elsewhere deeply buried beneath later beds. But the shield areas of the World, the Canadian, Baltic, Siberian, Indian, African, Brazilian Shields, etc., are made up of thousands of square miles of Pre-Cambrian rocks, which have been welded together by successive orogenies during Pre-Cambrian times. Since then the shields have acted as stable blocks and have been subjected

to such prolonged erosion that even the most resistant gneisses, quartzites and granitic rocks have been reduced to a peneplain.

It is the areas between these shields and the resistant blocks formed during the Caledonian and Armorican orogenies that have been invaded by the fluctuating seas of the past 500 million years. These seas were of two types, some were geosynclinal, others were *epicontinental*, in which relatively thin sediments were deposited and which have not been disturbed by subsequent earth movements. The lowland basins of today are formed in large part from the uplifted epicontinental seas of the past.

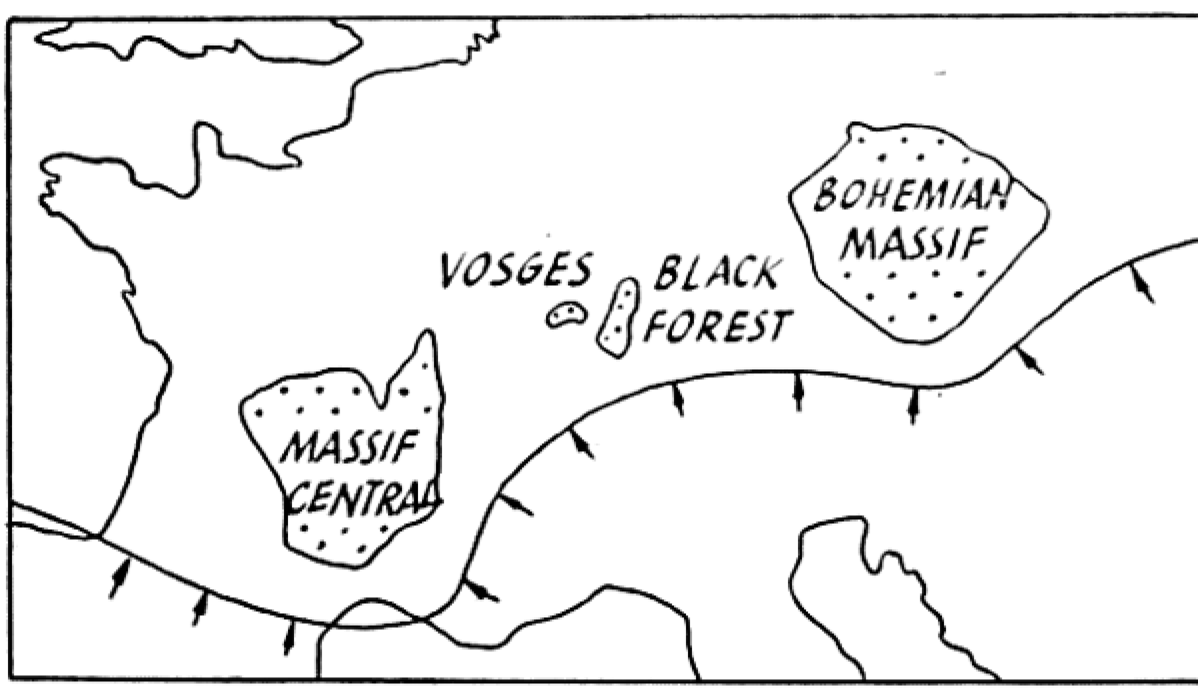


Fig. XV, 2.—Northward Front of the Alpine Fold Belt

Note the effect of the resistant blocks.

The major topographical and geological units of the existing continents are not only due to the effects of orogenic folding, vertical uplift and subsequent erosion. Vulcanicity is locally of great importance, giving rise to either extensive lava plateaux or to great volcanoes of the central type. In other areas, faulting has been the predominating factor. One of the major features of the Earth is the great system of *Rift Valleys*, extending for nearly 3000 miles from Syria to East Africa. They are bounded by parallel fault scarps or groups of scarps, usually about 35 miles apart, and between the scarps is a valley, often occupied by lakes, which is several thousand feet below the level of the surrounding country. The African Rift is unique only in its length, for closely comparable but much shorter structures are the Midland Valley of Scotland, the Rhine Rift or Graben and the Oslo Graben, which is mostly occupied by Oslo Fjord. The origin of such rifts is still uncertain. One view of the African Rift is that it was formed by tension, the bounding faults

being normal faults hading and downthrowing towards the valley. Others favour a compressional origin and believe that the country on either side has been pushed up steeply inclined and outward-hading fault planes. Unfortunately there has been so much land-slipping and, in places, volcanic activity along the fault lines that the direction of inclination of the fault planes does not seem to be determinable with certainty. More information is also needed as regards the nature of the rocks below the floor of the rifts, for one of the difficulties in accepting the tensional hypothesis is in explaining what has happened to the material which is supposed to have dropped like the 'keystone of an arch'.

Horsts are the contrast to the rifts. They consist of blocks, such as the Vosges and the Black Forest, composed of old folded rocks bounded by outward-throwing faults, so that the older rocks are faulted against younger strata. The resistant blocks, which controlled the pattern of the Alpine folds, were horsts made up of rocks folded during the Armorican orogeny, the Armorican fold belt having been subsequently dismembered by large scale faulting.

In other parts of the World, large scale faulting has caused not only simple up and down movement, but the tilting of the blocks between the faults. 'Basin and range' structures of the type found in the Great Basin region of the United States between the folded chains of the Rocky Mountains and the Coast Ranges were then produced.

Broadly speaking, we can regard the continents, including those parts such as the Baltic Sea and Hudson Bay which are submerged by epicontinental seas, as being built up of a combination of folded belts, shields and basins, which may be largely fault bounded. It has also been shown that the major orogenic episodes, which affected wide areas of the continents, were separated by long periods, many millions of years, of relative crustal quiescence. Only relative for today, 30 million years after the climax of the Alpine orogeny, the young folded mountains of the World are still in a state of instability, as is proved by the position of the belts of maximum earthquake and volcanic activity (Fig. XIV, 3).

Causes of Orogenesis

Another of the great unsolved problems of Geology is the nature of the forces responsible for orogenic movements. Numerous theories have been produced, the most important being those invoking either contraction of the Earth's surface, the development of sub-crustal currents or continental drift.

At first sight it would seem very plausible to suppose that the

Earth has been cooling throughout geological time, and that this has caused contraction of the crust which has been accommodated by the folding and compaction of the weakest belts, the geosynclines. But it is by no means certain that the Earth has been steadily losing heat; some hold that it has even gained heat. Even if cooling is admitted, then the rate of cooling must have gradually decreased and therefore the orogenic episodes should become more widely spaced in time, but this does not seem to be the case. Again, any hypothesis attempting to explain orogenic belts must also account for the other major features of the continents, such as the volcanic belts, the areas of fissure eruptions, the great rift valleys, etc. One can argue that contraction in one part of the crust must be accompanied by tension elsewhere, either then or at a slightly different time, but the time-space relation of the areas of compression and of tension seems to be far more complicated than can be explained by the simple theory of a contracting Earth.

In the theories of sub-crustal currents it is assumed that sufficient heat is generated beneath the continental masses by the disintegration of radioactive minerals (see p. 229) to render eventually the deeper layers plastic enough to flow slowly. When this occurs convection currents will be produced, forming a circulation similar to that developed in the atmosphere on a hot summer's day, when the position of the ascending currents is marked by towering cumuliform clouds, the areas of descending currents being cloud-free. The currents postulated in the Earth would be very slow moving, only a few centimetres a year, but they would be powerful enough to exert a considerable drag on the solid rocks of the overlying crust. Once this circulation was established, geosynclines would develop in the belts of convergence between the descending currents of two neighbouring convection cells (Fig. XV, 3). The great thickness of sediments accumulated in geosynclines is explained by the downward drag of the sialic rocks. Once current flow began it would gradually increase to a maximum with hot material of deep-seated origin moving relatively rapidly into regions of less density and cooler material being carried down to take its place. The main orogenic compression would occur at this phase of maximum drag, the roots of the mountains being formed and the rocks of the geosynclinal belt strongly compressed. But as the cooler material reached the bottom of the cells, the velocity of the currents would be reduced and finally they would come to rest when the convectional overturning was completed. It would be during this waning phase that isostatic uplift would cause the emergence of the mountain chains. Then after

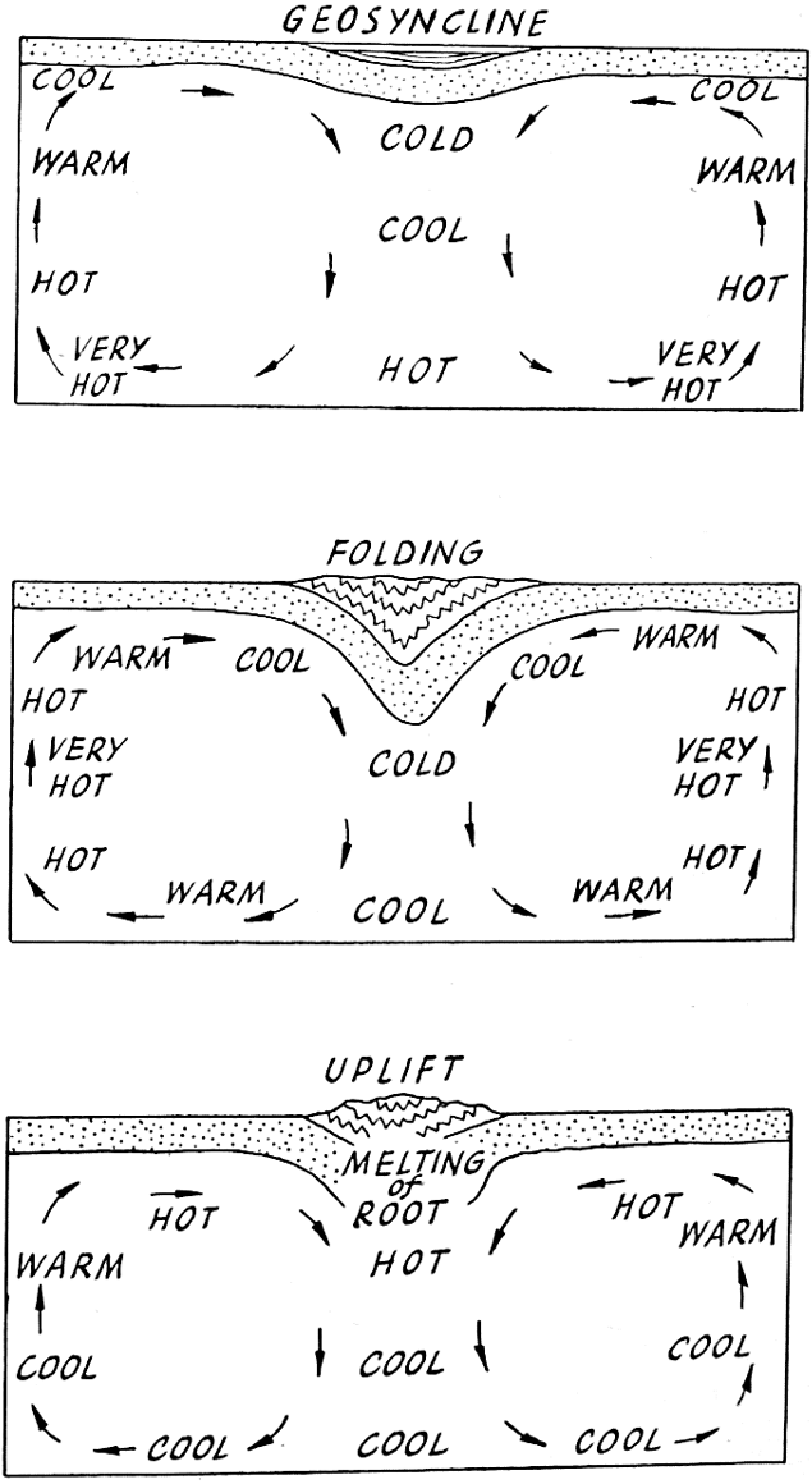


Fig. XV, 3.—History of an Orogenic Belt According to the Convection Current Hypothesis

a period of quiescence, convection cells would develop afresh in a different location and a new cycle would commence.

The advantage of this theory is that it attempts to account for the whole history of a mountain chain, from the formation of the geosyncline to the final uplift. The difficulty is our lack of sufficient knowledge of the nature and physical properties of rock material at depth to be sure that it would behave in the manner suggested.

Whilst some lateral movement of the continental masses is allowed for by the simple convection theory, it is only of very limited extent. The Continental Drift Hypothesis, on the other hand, postulates horizontal movements of thousands of miles. Taylor and Wegener, who independently developed the theory, argued that about 220 million years ago the sialic masses were all close together and that since then the American continents have drifted westwards with the Atlantic Ocean gradually widening from south to north, whilst the buckling of the western edge of the American continent against the sima of the Pacific Ocean produced the folded mountain chains of the Andes and the Rockies. In the same way the northward drift of India produced the Himalayas and other young mountain chains of Asia, whilst the drift of Antarctica and Australia has similarly folded the leading edges of these continents.

In support of this theory Wegener cited two main lines of geological evidence. He claimed that the correspondence of structures and distribution of certain fossils down the two coasts of the Atlantic Ocean was so close that they could only be explained if in the past the two coasts had been very much nearer together than they are today. Secondly he claimed that the presence of continental ice-sheets, about 220 million years ago, that had been moved in areas now so widely separated as South America, Antarctica, South Africa, Australia and India could only be accounted for if these areas had originally formed part of a 'Gondwanaland' continent. After the glaciation this continent had been disrupted into blocks which had drifted to their present positions. He further claimed considerable migration of the Poles, and explained the direction of ice movement, which was based on clear evidence, by placing the South Pole, at the maximum of the glaciation, on Gondwanaland (Fig. XV, 4).

Such sweeping ideas naturally aroused considerable controversy, which was mainly centred on two points. First the force that was responsible for drifting the continents. Wegener suggested separate causes for the northward drift from the poles and the western movement of America. The first he ascribed to the gravitational pull exerted by the bulge of the Earth round the Equator and the second

to the greater effect of tidal friction on the continents, which would cause them to lag behind the more depressed areas of the crust on a rotating Earth and therefore apparently drift westwards. Both these forces are realities but the geophysicists soon claimed them to be many million times too small to produce the effect postulated. Also they could not accept Wegener's argument that the sima of the ocean floors had so little strength that sialic masses of lighter density could plough their way through it.

Secondly there was the question of the validity of the geological evidence adduced for Continental Drift. If this was overwhelming,

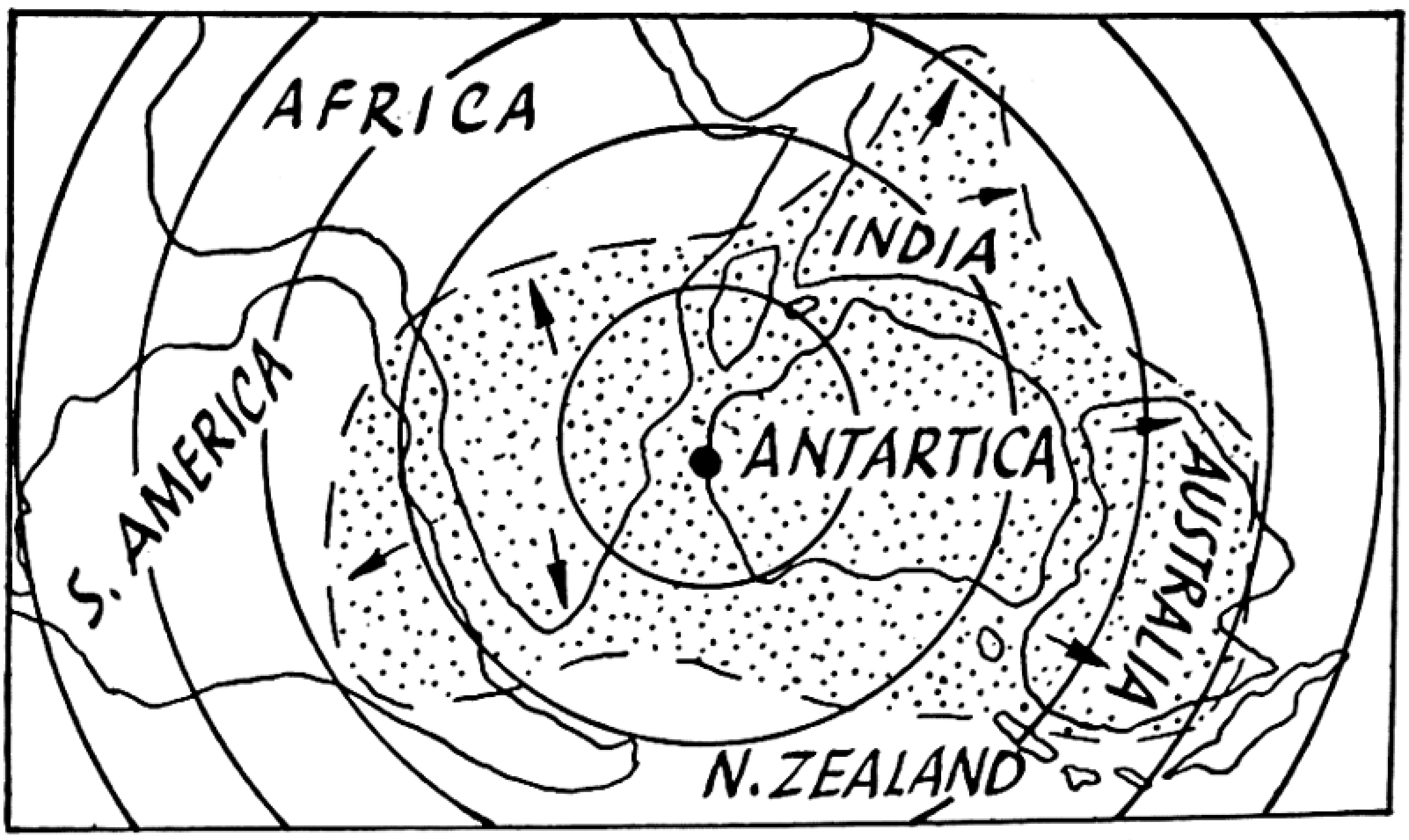


Fig. XV, 4.—Reconstruction of Gondwanaland (after Du Toit)

The stippled area was covered by ice, the arrows indicate the direction of ice movement as shown by striae, erratics, etc.

it could be argued that drift must have occurred and that the difficulty of providing the necessary motive force was due to incomplete knowledge of the physical characters of the Earth. Wegener was primarily a meteorologist, not a geologist, so his geological 'evidence' was soon shown to be open to criticism. Indeed the many opponents of the theory claimed that the 'fit' of the two coasts of the Atlantic was largely illusionary. The accuracy of the fit is very difficult to assess, for the present coast lines are merely temporary features and one must compare the continental margins, not coasts, and in doing so allowance must be made for a certain amount of rotation of the continents as they drifted apart. In addition there is the mid-Atlantic ridge, mainly submerged, but with the islands of the Azores, Ascension and Tristan da Cunha upon it. The more exact knowledge

of the geology of the two coasts that has become available since Wegener first published his theory in 1915 is in general not too favourable for his interpretation.

Wegener's geological evidence was not based only on structural similarities, for he laid much stress on the closely similar but unusual groups of animals and plants that had been found in the rocks of what he claimed to be disrupted fragments of Gondwanaland. Previously the answer to the problem of accounting for the occurrence of similar groups of land organisms in areas now widely separated by sea had been to suppose that they must have migrated across 'land bridges', in other words to assume that the ocean basins were not permanent features of the crust but that at some stages of the geological past land areas had arisen across the Atlantic or even the Pacific Ocean. Land bridges created more difficulties than they solved for an uplift of thousands of feet of a considerable area of the ocean floor must have meant, provided that the volume of water in the oceans did not change, widespread submergence of some adjacent area. Further, the absence of typical deep sea deposits in the rocks of the existing continents was strong evidence for the permanence of ocean basins. But if the continents had gradually drifted apart, then these similarities in plants and animals could be explained without the need of rapidly fluctuating land bridges.

Some botanists and zoologists therefore regard the Continental Drift hypothesis as solving many of their problems of distribution and it certainly seems that their support for the reality of drift, though not necessarily precisely in the directions claimed by Wegener, is not to be lightly disregarded.

Wegener also claimed that measurements of longitude showed that Greenland was drifting away westwards from Europe but more recent determinations have not confirmed this and most authorities now believe that the 'western drift' of Greenland is within the margin of error of the instruments used for the older determinations. International measurements of longitudinal difference have been made between a few points on various continents and they have not revealed any differences greater than the possible instrumental errors, so at present this evidence is entirely inconclusive.

If the possibility of Continental Drift is admitted, and certainly the Gondwanaland glaciation is extremely difficult to explain with the continents in their present position, there still remains the problem of the motive force. Some have extended the Convection Hypothesis by suggesting that if, at one particular period, the convection currents were unusually powerful, they would cause drift.

A continental block is thought to have broken in the middle over the ascending currents and the two parts to have drifted towards the descending currents, where mountain ranges close to ocean deeps would be formed, whilst great extrusions of plateau basalts would break out in the region of tension over the ascending currents.

But this theory does not account for the unquestioned evidence both of orogenic folding and of great extrusions of lava, at intervals, throughout geological time. The Pre-Cambrian rocks of the Canadian Shield, for example, have yielded evidence of, at least, three orogenic episodes, each of which must have rivalled the geologically recent Alpine orogeny. The Continental Drift Hypothesis, either as originally stated, or as modified by the introduction of convection currents, is primarily intended to explain the events of the last 220 or so million years and these earlier orogenies are left largely unaccounted for. The Contraction Theory does not suffer from this defect, for according to it the Earth has been cooling, not necessarily steadily, ever since the solidification of the crust and therefore orogenies are as likely, indeed are rather more likely, to have occurred during Pre-Cambrian as in later times.

SECTION E

Historical Geology (Stratigraphy and Palaeontology)

CHAPTER XVI

The Geological Time-Scale

GEOLOGICAL time is measured in millions of years. The formation of a peneplain or the deposition of the thousand feet or so of Chalk underlying London must represent a very long time. Geologists have long appreciated this and were greatly embarrassed when Lord Kelvin in 1883 calculated that the Earth must have taken only about 100 million years to cool from its original molten state to its present temperature. One vital factor was missing from Lord Kelvin's calculations. The existence of radioactivity had not been discovered.

Radioactive minerals are not stable like ordinary minerals, but undergo spontaneous disintegration, owing to the emission of atoms of helium and electrons. New radioactive substances are formed and the process continues through a chain of changes, until a stable end product, an isotope of lead, is produced. The period of disintegration of each of the radioactive substances is known. It varies at different stages in the chain, from fractions of a second to millions of years. This disintegration proceeds steadily, a fixed number of atoms being affected each minute and not in a series of sudden transformations from one form to another. The proportion of helium and lead that is present in a radioactive mineral is therefore a measure of how far it has proceeded along the chain, and hence of the time that has elapsed since that particular mineral was formed. Helium, being a gas, is liable to be lost, but the radioactive lead remains and can be measured by elaborate chemical analysis.

The age of the oldest known radioactive mineral, from Manitoba in Canada, is at least 3000 million years, so now geologists have immeasurably more time at their disposal than Lord Kelvin allowed them. Radioactive disintegration causes the liberation of heat and as

Lord Kelvin was unaware of this source of heat, his calculations were in error.

But radioactive minerals are extremely rare. The geologist has had to devise his own method, the Stratigraphical Table, of measuring the passage of time. He has done this by arranging the stratified rocks in the order in which they were deposited and then by dividing them into groups, each of which represents a distinctive period of time.

The Stratigraphical Table

In the closing years of the 18th century, William Smith (p. 15) began to draw up the geologists' scale, by working out the succession of the strata around Bath. By the middle of the last century a complete scale, adopted internationally, had been produced. Just as the historian divides the events of the last thousand or so years into dynasties and reigns, so the geologist uses eras and periods. The rocks deposited during an *Era* are known as a *Series* and those during a *Period* as a *System*.

Time is divided by the geologist into five Eras. Working back from the present, the Quaternary Era, which has only just begun, we speak of the Tertiary, Secondary and Primary Eras or, using another terminology, based on the type of fossils which are found in these rocks, we refer to the Cainozoic (Recent Life), Mesozoic (Middle Life) and Palaeozoic (Ancient Life) Eras. It is customary today to use the terms Tertiary, Mesozoic and Palaeozoic, the alternatives having fallen into disuse.

The nomenclature of the periods is of diverse origins. The *Quaternary* Era is usually divided into the Recent or Holocene Period and the older, Pleistocene (most recent) Period.

Sir Charles Lyell divided the *Tertiary* strata, by the percentage of recent shells found in the rocks of each system, into the Pliocene (more recent), Miocene (less recent), Oligocene (little recent) and Eocene (dawn of the recent) systems. The systems of the *Mesozoic* era were not christened in such a logical manner. The Cretaceous System was named after the Chalk (Latin *creta*), its most characteristic rock-type, the Jurassic, after the Jura Mountains, the site of much of the early work on these rocks, and the Triassic after the three-fold division of its strata in Germany.

For the *Palaeozoic* rocks, the terms Permian (after Perm in southern Russia), Devonian and Cambrian (Cambria the medieval term for Wales) are obviously chosen from places where the existence of these systems was first recognized. The Silurian and Ordovician

Systems were named after Celtic tribes which lived along the Welsh Border and fought valiantly against the Romans. The term Carboniferous System is clearly derived from the coal, which is so often found in its rocks.

The subdivision of the systems into smaller units, stages, need not concern us here.

The early geologists grouped together all the rocks beneath the Cambrian system as the *Pre-Cambrian* Series. Subsequent work, particularly in the shield areas, has shown that the Pre-Cambrian 'Series' is considerably thicker and must have taken a longer time to be deposited than the Palaeozoic and later series combined. In many areas it is possible to recognize an upper group of unmetamorphosed Pre-Cambrian rocks resting on strongly metamorphosed strata. The terms Proterozoic (earlier life) and Archaozoic (primaeval life) which are often applied to these two groups are misleading, for very few traces of fossils have been found in them, even in the Proterozoic rocks. It is better to use the terms Algonkian and Archaean.

The periods of orogenesis, which are major events in geological history, need to be placed in the Stratigraphical Table. A major orogeny has affected the Devonian and Carboniferous rocks of Devon and Cornwall, but the Permian and Triassic beds are not only unfolded but, as will be shown later, were formed by the erosion of a mountain chain. This orogeny can therefore be dated with precision as occurring in post-Carboniferous-pre-Permian times. It is named the Armorican orogeny after the Roman name for Brittany, where its effects were even more pronounced. The other orogenies, Caledonian and Alpine, are similarly named after intensely folded areas, in which it is possible to date on the Stratigraphical Table the time of maximum earth movement.

Radioactive minerals enable us to determine the duration of the eras and systems, provided that we can find sufficient number of radioactive minerals, whose age in millions of years can be determined and whose time of formation can be fixed on the stratigraphical scale. It is not always possible to be as precise as we have been in dating the Armorican movements, often the age of the mineral only can be given, for example as post-Carboniferous-pre-Tertiary. Sufficient fixed points have, however, been found for the Stratigraphical Table to be dated as shown on page 232.

TABLE XI

THE GEOLOGICAL TIME-SCALE

Eras	*Periods*	*Duration*	*Time from present in millions of years*
Quaternary	Holocene	10,000 years	1
	Pleistocene	1 million years	1
Tertiary	Pliocene	14 million years	15
	Miocene	20 million years	35
	Alpine Orogeny		
	Oligocene	10 million years	45
	Eocene	25 million years	70
Mesozoic	Cretaceous	70 million years	140
	Jurassic	30 million years	170
	Triassic	25 million years	195
Palaeozoic	Permian	25 million years	220
	Armorican Orogeny		
	Carboniferous	55 million years	275
	Devonian	45 million years	320
	Caledonian Orogeny		
	Silurian	30 million years	350
	Ordovician	70 million years	420
	Cambrian	100 million years	520
Pre-Cambrian		approximately 2500 million years	3000

CHAPTER XVII

Fossils

FOSSILS are the remains, or traces, of organisms which lived under conditions different from the present. The last clause is necessary, for the fragments of pots obtained from a round barrow in Britain or from an excavated palace in Crete or the human skeletons buried by the volcanic eruption which overwhelmed Pompeii in A.D. 79 are not fossils. They are too recent and are the concern of archaeologists. The Pleistocene Period ended with the retreat of the ice after the last glaciation, so it is at the beginning of the Holocene Period that present conditions begin and the geologist hands over to the archaeologist.

The chances that any particular organism living in, for example, the Carboniferous Period should be preserved today as a fossil are exceedingly small. In the first place it must have been buried very rapidly after its death to have avoided decomposition or having been broken up by scavengers. Even if the organism was buried, it might have been destroyed subsequently in several different ways. If it was enclosed in a porous stratum, all trace of it might have been removed by percolating water or the rocks containing it might have been metamorphosed and so recrystallized that all traces of organic structures were obliterated. Finally that particular stratum must be exposed today, so that its fossils can be collected.

Whole Organism Preserved

Fossils are found preserved in a variety of ways. Very exceptionally the organism is preserved whole. This can only occur if it was sealed from decay immediately after death. Some of the mammoths, which wandered over the frozen tundras of Siberia towards the close of the Pleistocene Period, were trapped in partially frozen quagmires.

By their struggles they sank down into ground, which has been frozen ever since. They have been preserved so well in cold storage that their discoverers were able to sample mammoth steak! The pebbles of amber, which are to be found in the Oligocene beds of the south-eastern shores of the Baltic, sometimes contain complete fossil insects, which had been trapped in and then enveloped by the resin oozing from coniferous trees. The trees died and decayed, but the resin hardened into amber.

Hard Parts Preserved Unchanged

In Tertiary rocks, in particular, we find myriads of shells, the soft parts of the shell-fish having decayed, but the hard parts have been preserved unchanged. But even then it is often seen that in the same bed oyster shells are perfect, whilst other shells are crumbling and flake on the surface. The shells are all composed of calcium carbonate but organisms can secrete this either in the form of calcite or of aragonite. Aragonite is much less stable and more easily soluble than calcite, hence the difference in the preservation of the calcite shells of the oysters and the aragonite shells of the other forms.

It therefore follows that it is the most durable and least soluble parts which will be preserved longest. The teeth of vertebrates, such as fish, composed of calcium phosphate, survive long after the bones have disappeared.

Petrifactions

In the older rocks, fossils are often preserved by mineralization as petrifactions. Mineral matter, dissolved in percolating water, has been deposited to replace the calcareous or carbonaceous parts of the organisms. If this replacement has been gradual enough, really molecule by molecule, then all the detail will have been preserved. Some of the most exquisite of fossils are the cones and pieces of wood, now preserved in silica, which form the silicified forests of Arizona and Patagonia. Other common forms of replacement are by iron pyrites or by limonite.

Moulds and Casts

But percolating water may dissolve away the calcareous organisms more easily than the rock enclosing them. If this rock is strong enough not to fill in the cavities thus formed, the fossils will be represented by moulds and casts. Moulds are the impressions of the outer surface of the organism, whilst casts consist of the matrix that has filled the interior of the organisms after the decay of its soft parts. A mould

can be infilled with plaster or a dental composition and the external features of the organism restored. Casts are even more useful. The structures of the inside of a shell are often of much greater interest than the ornamentation of its exterior. If the specimen is preserved as a shell in a hard rock, it is usually a very difficult matter to remove the shell so as to expose its internal features. In a cast, however, the shell has already been removed and the internal features are easily studied.

The space between the mould and cast may, however, be infilled by mineral matter at some time after the dissolving of the original shell. This is not petrifaction, for the original material has not been replaced; it has been dissolved away and the result is often far from satisfactory. The secondary mineral is crystalline and usually assumes a shape that is not identical with that of the cavity. For example, the silicified shells found in the Upper Greensand of East Devon often show orbicular markings, which are not original, but are due to cavities having been infilled by chalcedonic silica with the growth of beekite, a form of silica with a concentric structure, on and in the walls of the cavities.

Traces of Organisms

The last kind of fossils are the traces of organisms. Sometimes one finds casts of footprints made by creatures walking across damp mud, which was baked hard by the sun before the deposition of the next layer. One may find the fossilized casts of worms or the burrows of organisms infilled by a slightly different matrix from the surrounding rock. In parts of the Triassic System almost the only traces of past life are footprints, but by studying their size, length of stride, the way the feet were set down, etc., much can be inferred as to the kind of creature that made them.

The Completeness of the Fossil Record

Clearly one cannot expect the fossil record to be completely representative of all the forms of life of the past. It was only organisms with hard parts which stood a reasonable chance of being preserved. It is very exceptional to find traces of soft-bodied creatures. Lithographic Stone, an unusually even-textured limestone, quarried from the Upper Jurassic strata of Solenhofen in Bavaria, is world famous not so much for its use in lithography, as for the rich fauna, including many soft-bodied forms like jellyfish and worms, which it has yielded. In 1938 fishermen trawling in South African waters caught an unusual-looking fish 5 feet in length. It was of a type which had been

regarded as extinct for the past 50 million years. But since then other specimens have been caught near Madagascar and one wonders how many more 'extinct' forms may be living in the seas.

Our knowledge of the marine and lacustrine faunas of the past is much more complete than that of the forms which lived on land. Marine forms, particularly those which burrowed into the sea floor, were much more likely to be covered quickly by sediment than terrestrial forms.

But even allowing for the fact that the fossil record can never be complete, owing to the chances against fossilization, it must be remembered that only a few well preserved specimens of any creature are needed for its thorough study.

The Chief Types of Organisms Found Fossil

Organisms normally belong either to the Animal or the Plant Kingdom but there are certain very primitive types, such as the diatoms, which show some of the characters of both animals and plants. Each Kingdom is divided into a number of major groups or phyla, the phyla into classes, the classes into orders, the orders into families, the families into genera and the genera into species, the smallest division usually recognized. A species is a group of closely related organisms, with a number of characteristics in common and capable of interbreeding.

Scientific nomenclature of organisms, at first sight, appears rather terrifying. It is designed for international use and was devised by the great Swedish naturalist Linnaeus (1707–1778). Each species has a double name, derived, often very curiously, from Latin or Greek. The first word is the generic and the second the specific name. Thus *Homo sapiens* means that Man belongs to the genus Homo and the species sapiens (wise), whilst the extinct but not very different 'Neanderthal Man' is called *Homo neanderthalensis*. 'Peking Man', on the other hand, differs sufficiently from *Homo* to be placed in a different genus, *Pithecanthropus pekinensis*. Similarly for invertebrates, *Micraster cor-anguinum*, a common fossil of the Chalk, is a sea urchin of the genus *Micraster* (little star) and the species *cor-anguinum* (heart-shaped), whilst *Micraster cor-testudinarium* (tortoise-shaped), also to be found in the Chalk, belonged to a different species of the same genus.

We are not concerned here with such small units as genera and species. They are for the attention of specialists. In the succeeding pages are given the salient features of the main groups (phyla or classes only) of organisms which are found fossil.

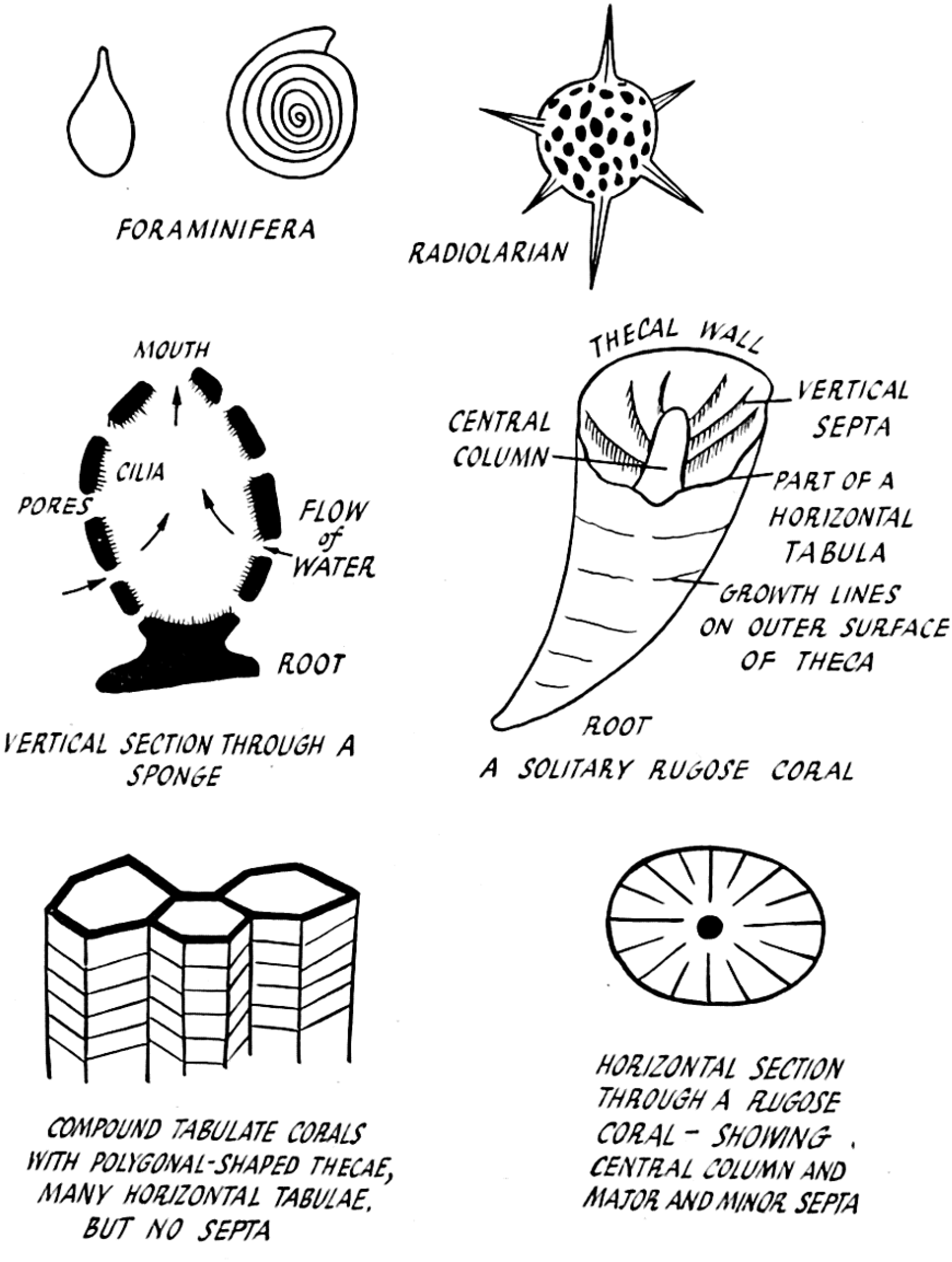


Fig. XVII, 1.—Protozoa, Porifera and Coelenterata

PHYLA OF THE ANIMAL KINGDOM

1. *Protozoa* (first animal) are the most primitive group, being formed of a single cell. Two classes of protozoans, the Foraminifera and the Radiolaria, secrete a shell, often of the most delicate tracery. In the majority of the *Foraminifera*, the shell is composed of calcium carbonate and in most of the *Radiolaria* of silica. They are marine, mainly planktonic and usually minute, though some of the 'giant' foraminifera exceed 1 inch in diameter (Fig. XVII, 1).

Range Cambrian to Recent.

2. *Porifera* (passage bearers). The simplest of the Metazoans or multicellular forms. Mainly vase-like in shape, the sides of the vase being perforated by minute *pores*, through which a current of water is wafted by vibrating hairs or *cilia*. The water passes out of the mouth of the vase, any contained nutritive material having been absorbed during its passage through the *pores*. The walls of the vase are supported by a skeleton, which may be of a leathery substance in the bath sponges, but in other forms is composed of tiny rods or *spicules* of calcium carbonate or opaline silica (Fig. XVII, 1).

Benthonic forms, mainly marine, ranging from the Cambrian to Recent.

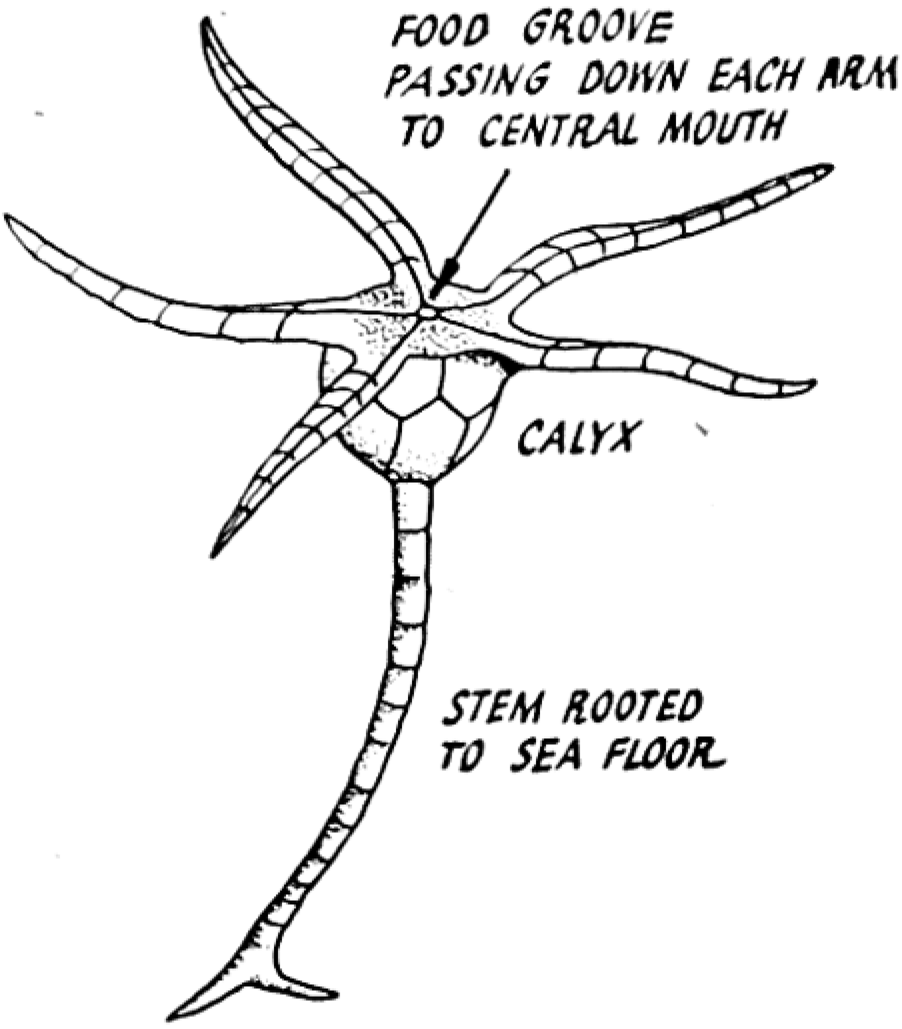
3. *Coelenterata* (hollow stomach). Forms with a mouth, ringed by tentacles and opening into a stomach. They occur either as *polyps* with sac-like bodies as in the sea anemones, corals and hydroids, or as umbrella-shaped *medusae* as in the jellyfish.

A very important fossil class are the *Anthozoa* (flower animals) or the Corals, which have a skeleton of calcium carbonate. The walls of the polyp are supported by a cup-shaped or cylindrical *theca*. Inside the theca is some combination of radially arranged vertical plates or *septa* and horizontal *tabulae*, whilst there is often a central and vertical *axial column*. Some corals are solitary (separate individuals), whilst others are colonial, consisting of a colony of polyps connected together and building up a massive skeleton, the top of which is perforated by the thecae.

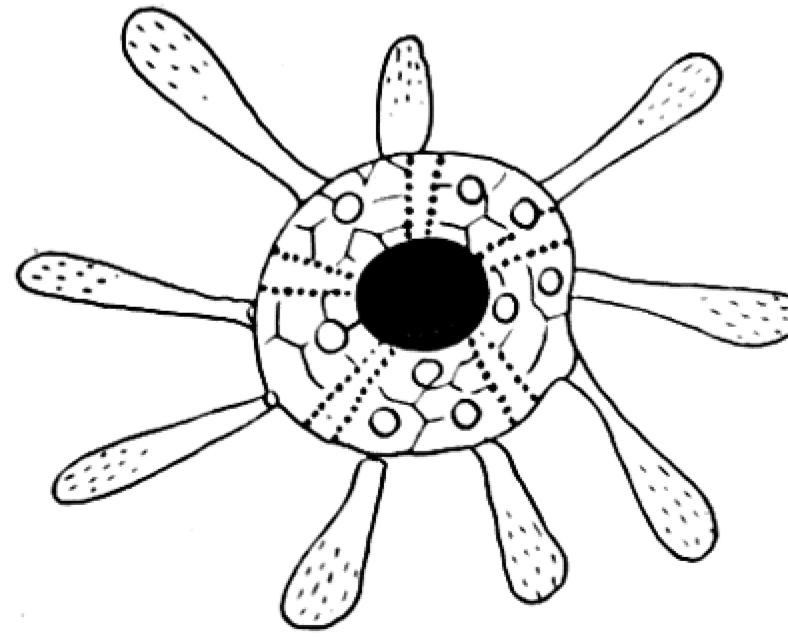
Palaeozoic corals belong either to the Rugosa or the Tabulata. In the *Rugosa* septa and often an axial column are well developed, whilst in the *Tabulata* the axial column is missing, septa are either very short or absent, but tabulae are prominent. The relation of these two extinct groups to the Mesozoic to Recent *Hexacorals*, with very prominent septa, is uncertain.

Benthonic and exclusively marine (Fig. XVII, 1).

4. *Echinoderma* (spiny-skinned animals). Exclusively marine forms usually with a calcareous skeleton. They are divided into the fixed

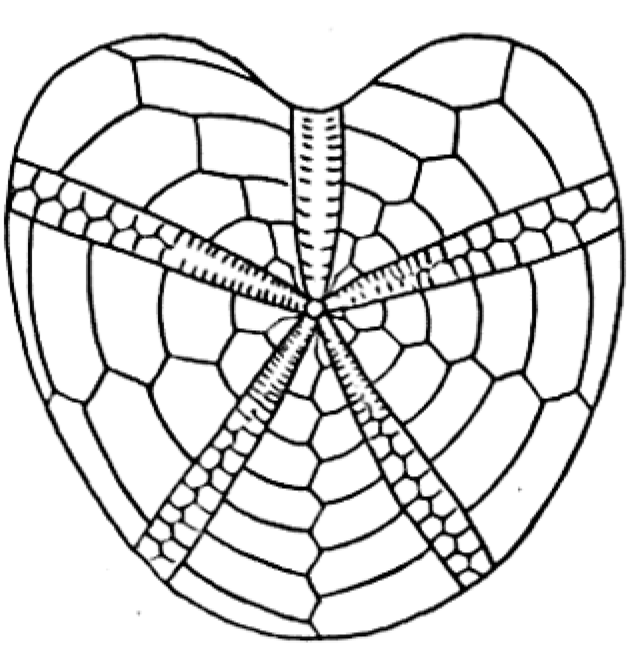


A CRINOID WITH ARMS OUTSPREAD FOR FEEDING. BOTH ARMS AND STEM ARE COMPOSED OF BEAD-LIKE OSSICLES.

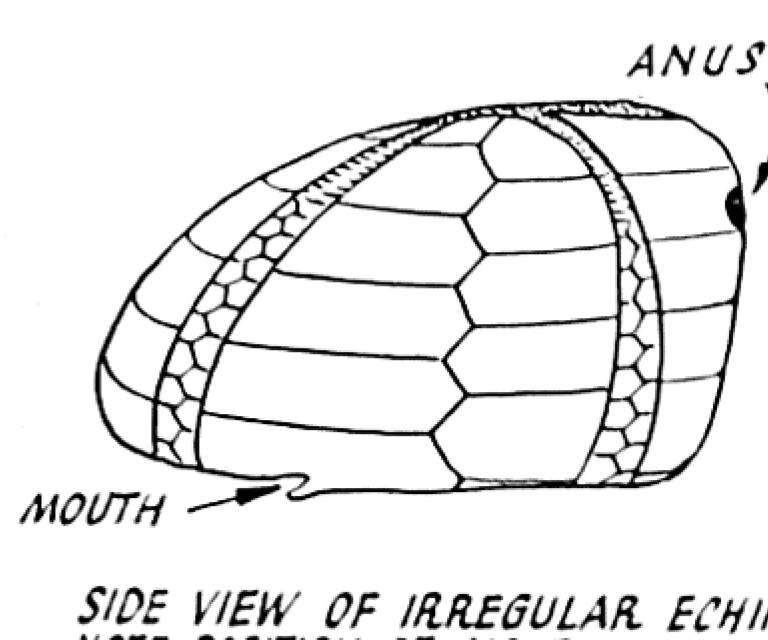


REGULAR ECHINOID

BOTTOM VIEW SHOWING CENTRAL MOUTH (BLACK) NARROW AMBULACRAL AREAS WITH PORES SEPARATED BY WIDE INTERAMBULACRAL AREAS NOTE LENGTH OF SPINES, ATTACHED TO ROUNDED BOSSES ON AREAS



TOP VIEW OF AN IRREGULAR ECHINOID NOTE BILATERAL SYMMETRY AND ABSENCE OF SPINES



SIDE VIEW OF IRREGULAR ECHINOID NOTE POSITION OF MOUTH AND ANUS

Fig. XVII, 2.—ECHINODERMA

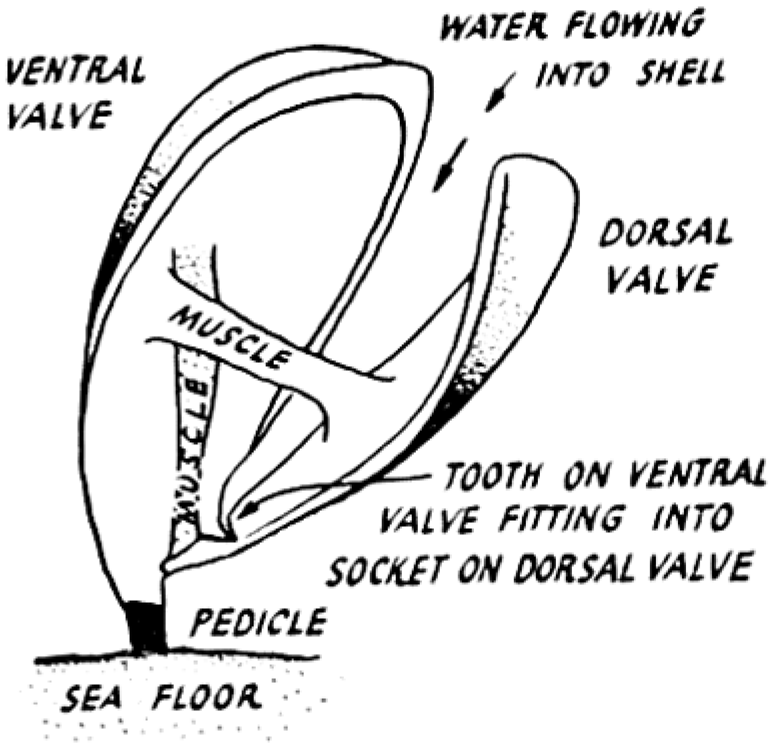
group, the *Pelmatozoa*, including the Crinoids (sea lilies) and the free-moving *Eleutherozoa*, including the Echinoids (sea urchins) and the starfish. In the Crinoids the organs are contained in a cup or *calyx*, which is attached to the sea floor by a long stem composed of disclike *ossicles*. Diverging from the upper surface of the cup are 5 or multiple 5 arms, which are spread out for feeding. Vibrating cilia cause a current to flow down each arm towards the mouth on the upper surface of the calyx (Fig. XVII, 2).

Palaeozoic crinoids were fixed in adult life, but certain Mesozoic to Recent forms were planktonic.

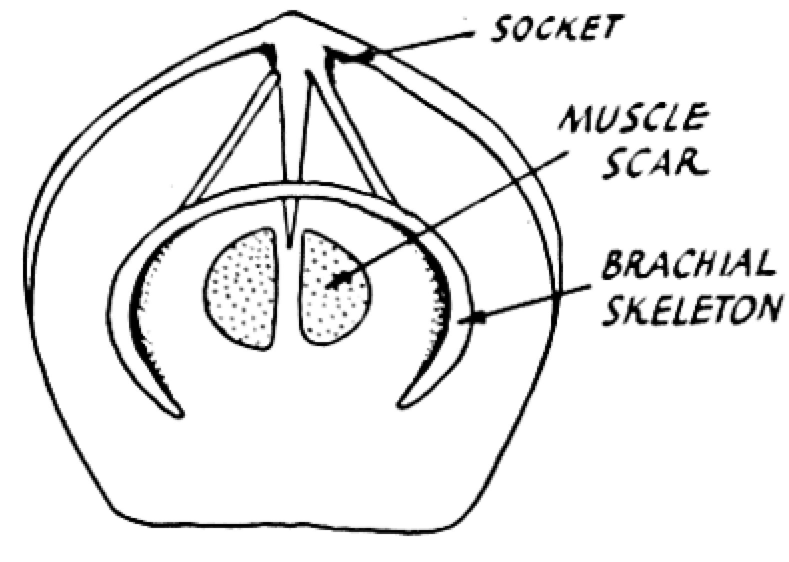
The *Echinoids* have a thin shell or test, which may show radial symmetry (Regular Echinoids) or bilateral symmetry (Irregular Echinoids). The test is composed of five rows of *ambulacral* plates, perforated by pores for the tube feet, used for movement. The ambulacra are separated by rows of *interambulacral* plates. In the Regular Echinoids the plates carry stout spines, whilst the large mouth is central on the under surface, with a large anal opening for waste products above it. These forms were scavengers crawling over the sea floor. Irregular Echinoids either buried themselves in the soft ooze or lived in shallow water. Their test is usually flattened with a wide base, spines are very slender or absent, whilst the anus and mouth are not central, but may have moved to the sides of the test and the ambulacral pores are usually restricted to the upper surface of the test (Fig. XVII, 2).

The other classes of Echinoderms, such as the Stellieroids (star fish), the Cystids and the Blastoids are too rare to be described here.

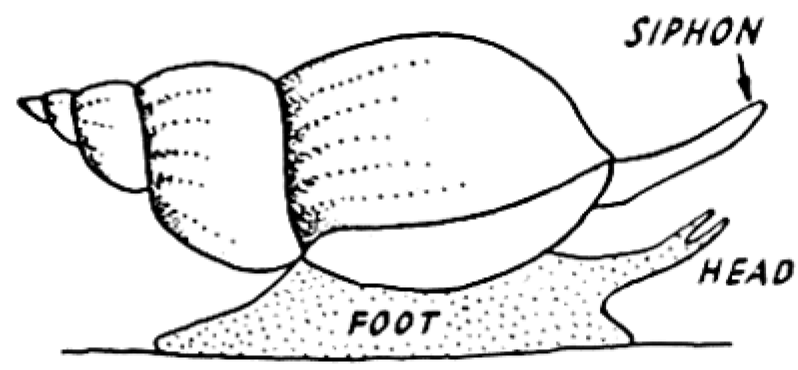
5. *Brachiopoda* (arm-foot). Exclusively benthonic marine forms whose soft parts are enclosed in two convex shells or *valves*, which are unequal in size but symmetrical. In the more primitive forms, the *Inarticulata*, the valves are composed of an organic substance, chitin, but in the advanced *Articulata* they are calcareous. Brachiopods were fixed by a stout *pedicle*, which in the Inarticulata usually passed out between each valve, but in the Articulata the pedicle opening was entirely in the larger (*ventral*) valve. The creature fed by opening the anterior part of the shell a fraction, so that cilia could cause a current to flow into the shell. The valves were opened and closed by sets of muscles. In the Articulata, the valves were guided into place by a pair of *teeth* on the ventral valve fitting into sockets on the *dorsal* valve, but in the Inarticulata these are absent and the muscular system is more complex. In the more advanced of the Articulata, the arms or *brachia*, which are used for respiration and feeding, are



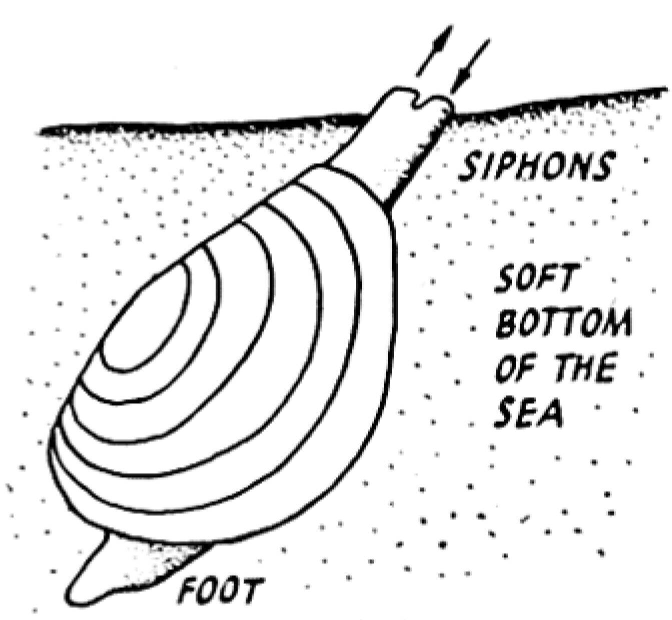
AN ARTICULATE BRACHIOPOD IN LIVING POSITION. THE GAPE BETWEEN THE VALVES IS MUCH EXAGGERATED AND THE VALVES HAVE BEEN CUT AWAY IN FRONT



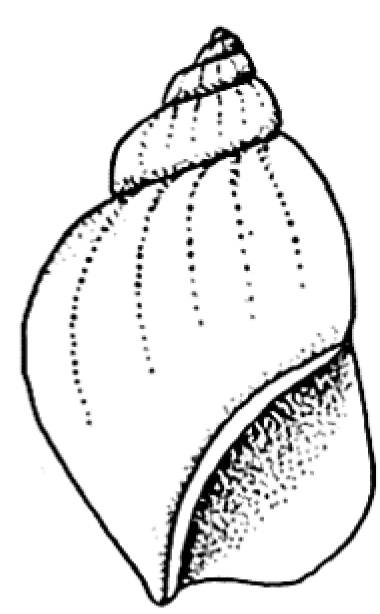
INTERIOR OF DORSAL VALVE OF AN ARTICULATE BRACHIOPOD



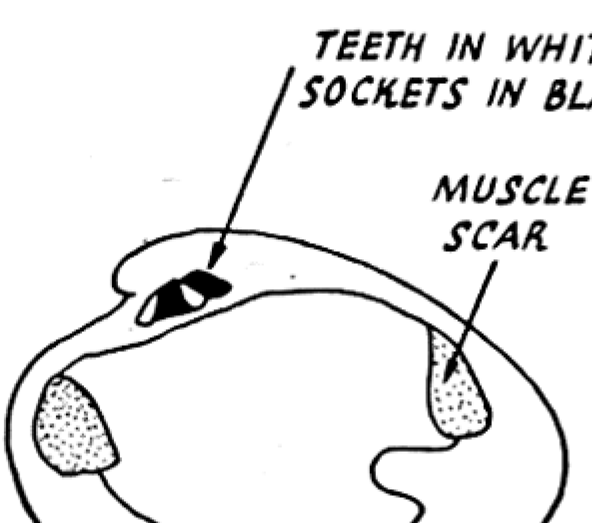
A WHELK (A TYPICAL GASTROPOD) CRAWLING OVER THE SEA FLOOR



A BURROWING LAMELLIBRANCH IN LIVING POSITION



A GASTROPOD SHELL



INTERIOR VIEW OF RIGHT-HAND VALVE OF A LAMELLIBRANCH

Fig. XVII, 3.—Brachiopoda, Lamellibranchiata and Gastropoda

supported on a *brachial skeleton*, either a loop or a spire, attached to the inside of the dorsal valve (Fig. XVII, 3).

Range Cambrian to Recent.

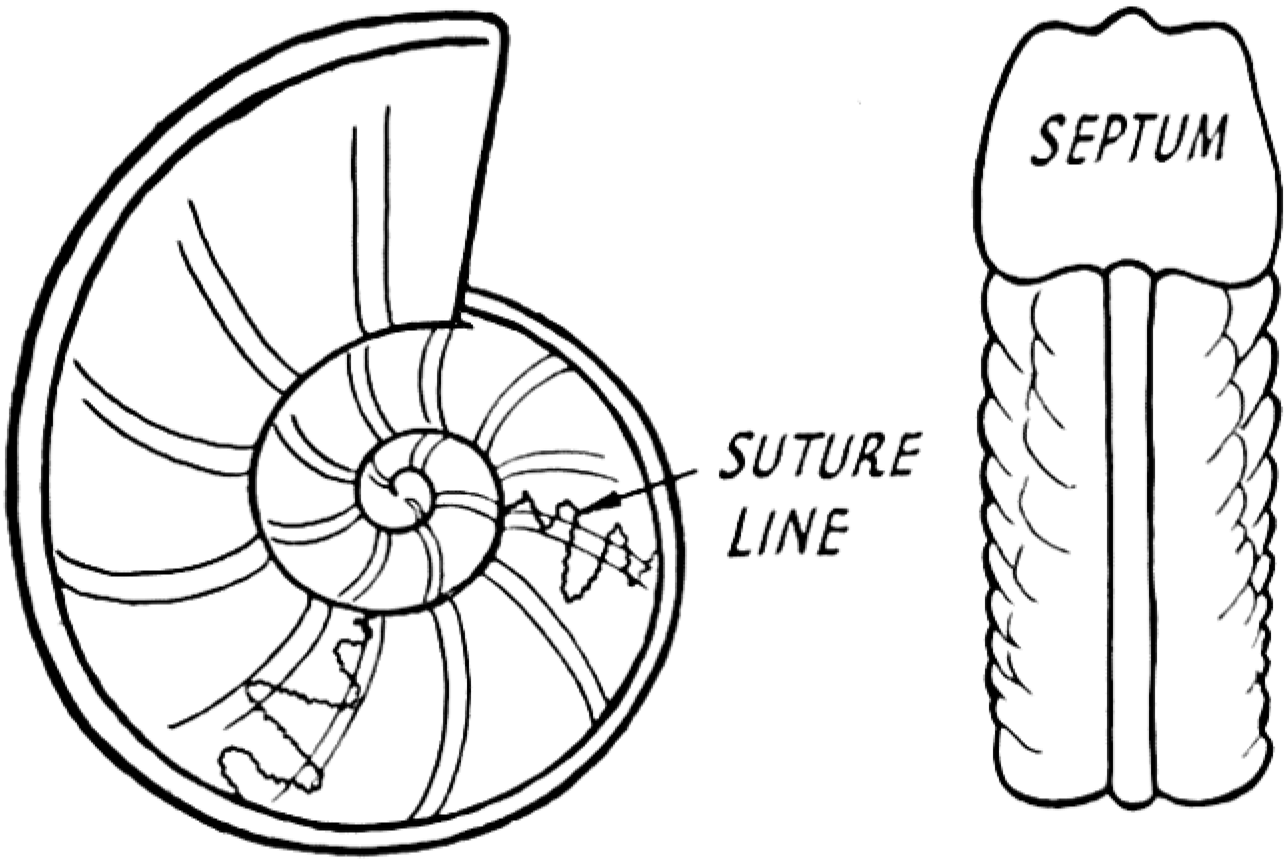
6. *Mollusca* (soft nut within a shell) are divided into several classes. *Lamellibranchiata* or *Pelecypoda* are bivalves like the Brachiopods, but have more complex soft parts with a foot for crawling on and a pair of tubes or siphons for respiration and feeding. The two valves, which are placed on the sides of the body, are, normally, equal in size and asymmetrical about the plane at right angles to them. Teeth and sockets are present on both valves. Certain forms, such as oysters, did not crawl over the sea floor but were sessile and the valve on which they rested became larger than the other. Other lamellibranchs burrowed into the soft mud. Their valves became elongated and gaped at the anterior end for the protrusion of the foot and at the posterior end for the passage of the siphons (Fig. XVII, 3). Lamellibranchs lived in either marine or fresh water and range from the Lower Palaeozoic to the Recent.

Gastropoda are univalves with an aragonite shell which is usually coiled in a spiral and is often elaborately ornamented. Snails are typical gastropods, crawling on a large foot, and having a distinct head, eyes and a rasplike tongue (Fig. XVII, 3). Those living in water breathed with gills, but those living on land have developed lungs. They are either herbivorous or carnivorous and are today a most varied group.

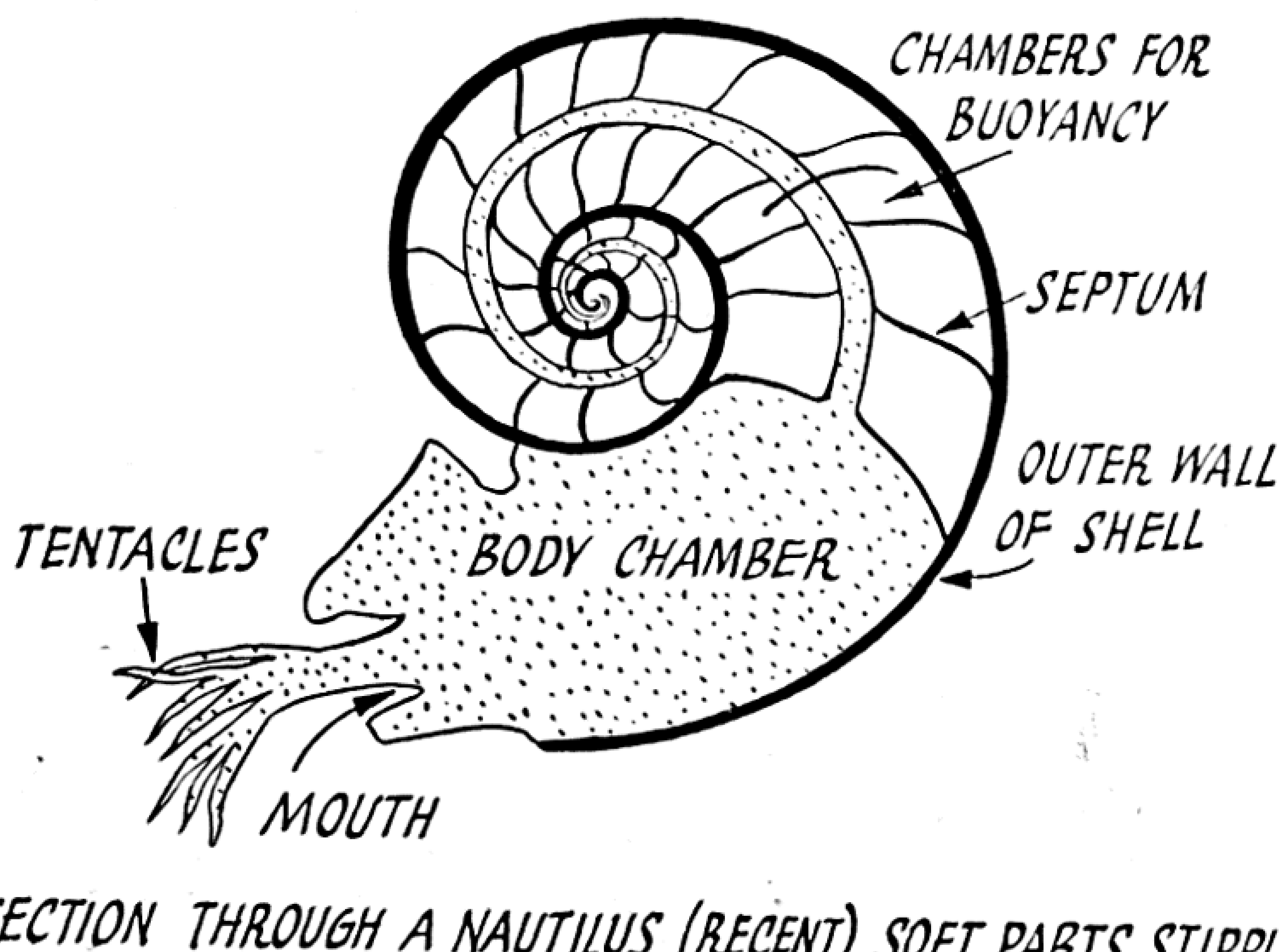
Cephalopoda include two well-known fossil groups, the Ammonites and the Belemnites.

The *Ammonoidea* had a thin, chambered aragonite shell which is usually coiled in one plane. The mollusc lived in the outer chamber, the inner chambers giving it buoyancy. Many tentacles surrounded its mouth, but they probably did not bear suckers, as do those of the modern octopus, which is a completely soft-bodied cephalopod. The partitions or *septa* between the chambers met the wall of the shell along a line known as the *suture*. In the Nautiloids (Lower Palaeozoic to Recent) the sutures were straight, in the Goniatites (Upper Palaeozoic) they were angular and in the true Ammonites (Mesozoic only) the sutures were most elaborately frilled (Fig. XVII, 4). After death the chambers became filled with matrix, making it difficult to realize that the Ammonoids were nektonic marine forms.

The *Belemnites* were also marine nektonic forms restricted to Mesozoic strata. They resembled the modern squid in having a stream-lined body with a ring of large tentacles round a parrot-like beak. They must have been very active carnivorous forms. Entirely



SIDE AND END VIEWS OF AN AMMONITE
THE FRILLED SUTURE LINES CAN BE SEEN WHERE THE RIBBING ON THE OUTSIDE OF THE SHELL HAS BEEN WORN NEARLY AWAY



SECTION THROUGH A NAUTILUS (RECENT) SOFT PARTS STIPPLED

Fig. XVII, 4.—Ammonoidea

enclosed by the body was the pointed *guard*, composed of radiating fibres of calcite (Fig. XVII, 5).

7. *Arthropoda* (jointed-foot) are the most highly organized of the invertebrata (backboneless creatures).

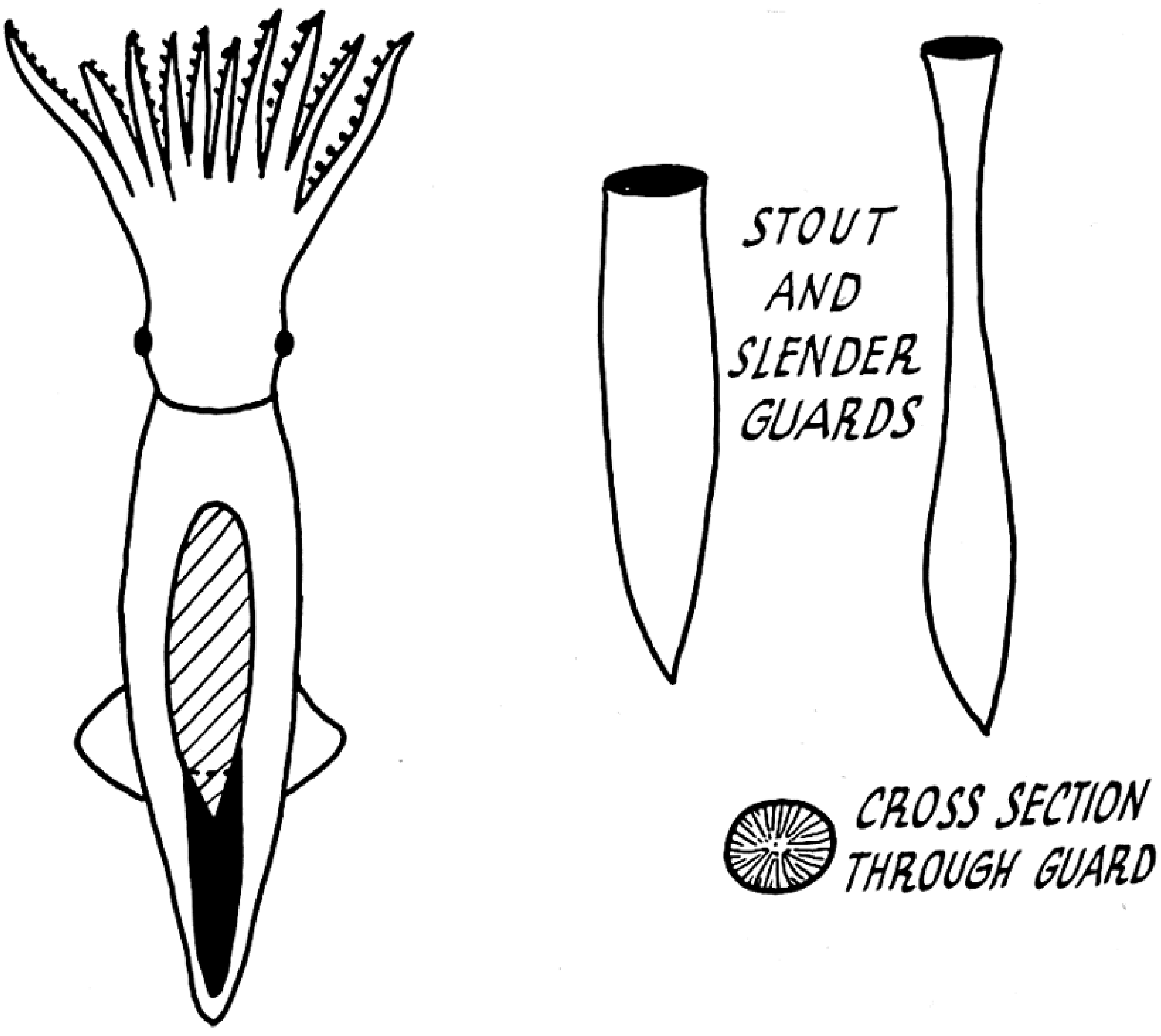


Fig. XVII, 5.—Belemnoidea

Restoration of a belemnite showing the position of the hard parts entirely within the body. The guard (solid black) is often preserved, the pro-ostracum (lined) only very occasionally.

Butterflies, crabs, scorpions, flies, etc., are only very occasionally found fossil, but in the Palaeozoic strata remains of an extinct class, the *Trilobita*, are relatively common. Normally only the chitinous back parts are preserved. These show two well-marked longitudinal grooves, hence the name Trilobites. The *head shield* usually bears a pair of many-lensed eyes, the body or *thorax* consisted of a large number of segments, which could move on each other, enabling the creatures to roll up like a modern wood louse. The tail or *pygidium* consisted of a number of segments fused together and sometimes ended in a spike.

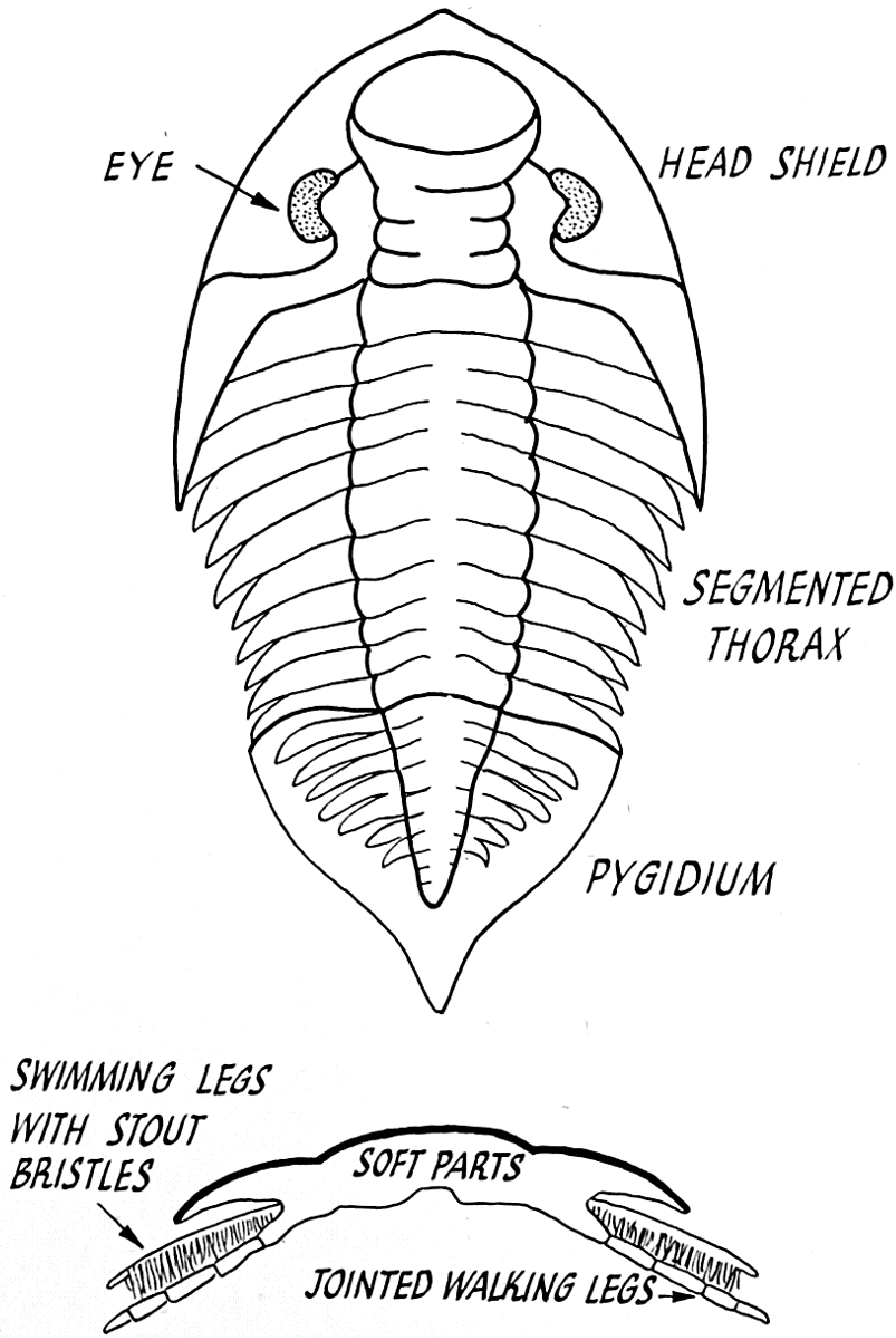


Fig. XVII, 6.—Trilobita

The undersurface was not hardened and hence is rarely preserved, but beneath each segment were two pairs of limbs, one for walking and the other flattened and with a row of bristles for swimming. Beneath the head shield were several pairs of mandibles for breaking up the food and passing it into the mouth. Like most other Arthropods, trilobites moulted periodically and then grew larger hard parts. Well-marked cracks on the head shield to facilitate moulting are called *facial sutures* (Fig. XVII, 5).

They were entirely marine nektonic creatures and were probably carnivorous and most effective scavengers.

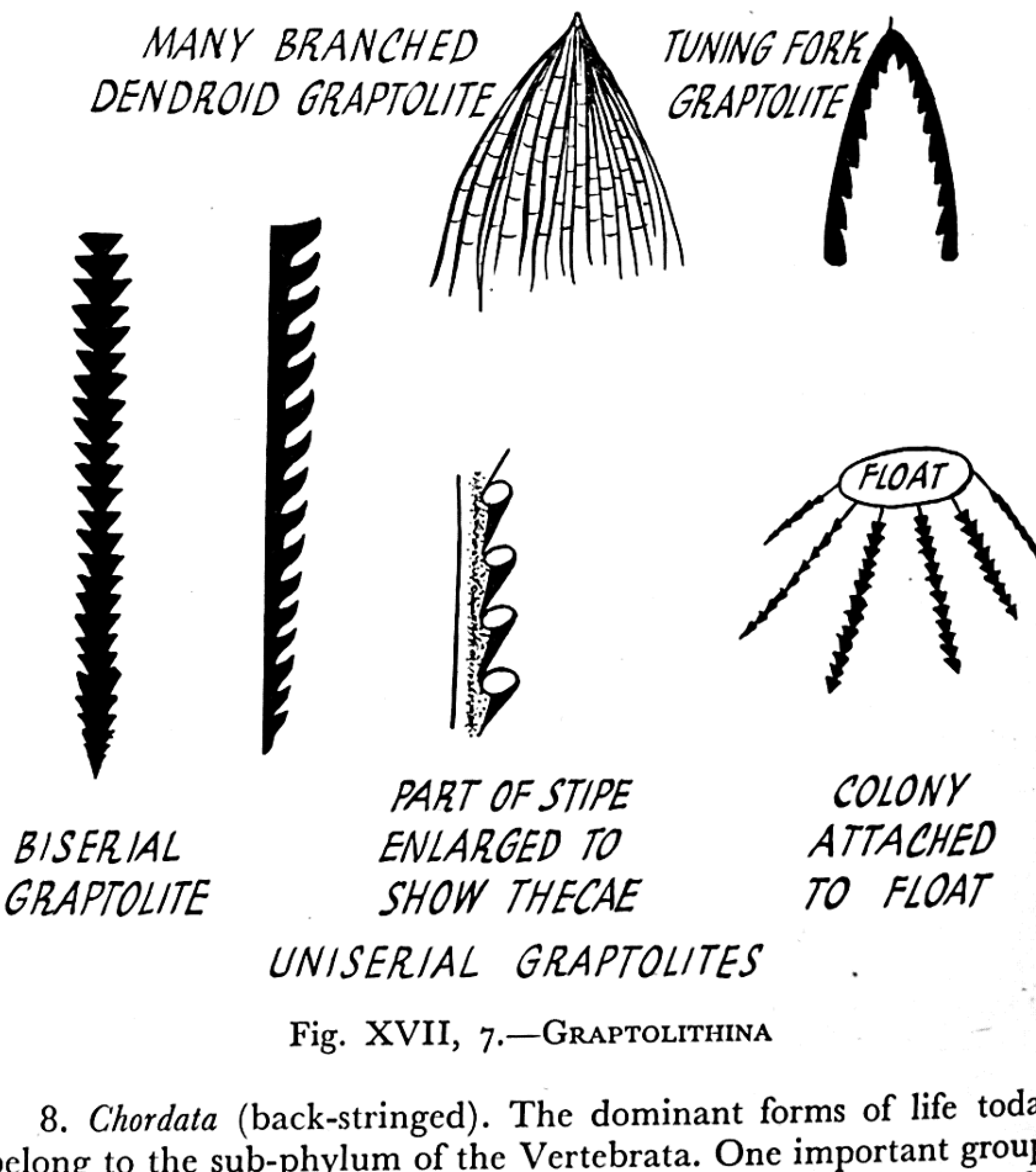


Fig. XVII, 7.—GRAPTOLITHINA

8. *Chordata* (back-stringed). The dominant forms of life today belong to the sub-phylum of the Vertebrata. One important groups of fossils, the Graptolites, have recently been shown to belong to the sub-phylum of the *Hemichordata. Graptolites*, which were marine and are restricted to the Palaeozoic rocks, had a chitinous skeleton. They

were colonial forms, consisting of numerous polyp-like individuals, each occupying a *thecal cup*, set either on one or both sides of a long branch or *stipe*. Along this stipe ran stolons similar to those of the other Hemichordata. Some Graptolites were attached to the sea floor, but the majority were planktonic, a number of stipes hanging beneath a large float or *cyst* (Fig. XVII, 6).

The *Vertebrata* are divided into the following classes:

Pisces or Fish with a cartilaginous or calcified backbone, fins, a well-developed tail and usually toothed jaws. The teeth, which are the parts most often preserved, may be either pointed for biting or flattened, as in the rays, for crushing molluscs.

Amphibia have developed from certain fish. The fins have become legs and lungs have replaced gills. But the Amphibia have not completely escaped from the water, for they must return there to breed.

Reptilia, on the other hand, laid eggs and could therefore bring forth their young on land. Freed from the need to spend part of their life in water, they developed in the Mesozoic Era an amazing range of forms, with their limbs adapted for many purposes, swimming, walking and even flying (Fig. XVII, 7). From certain reptiles developed the warm-blooded *Aves* or Birds.

Mammalia, which also developed from the Reptiles, protect their young in the mother's womb and are warm-blooded, which means that they are capable of more sustained activity than the cold-blooded reptiles. Dwelling mainly on land, their remains are not often preserved.

The Groups of the Plant Kingdom

1. *Algae*, including the Sea Weeds. Primitive plants without true roots, stems or leaves. Certain algae secrete skeletons of calcium carbonate.

2. *Pteridophyta*. Fernlike plants with roots, stems and large leaves (fronds). Reproduction is normally by spores, but the extinct *Pteridosperms* bore simple seeds on fernlike leaves.

3. *Gymnosperms* (naked seeds). Woody perennial plants without a protective covering for their seeds.

They include the following orders:

Coniferales, represented today by Fir, Pine, etc.

Cycads, which are much less important today than they were in the Mesozoic Era. Palmlike in appearance, they had stout stems crowned with a rosette of large leaves, amongst which were the seed-bearing cones.

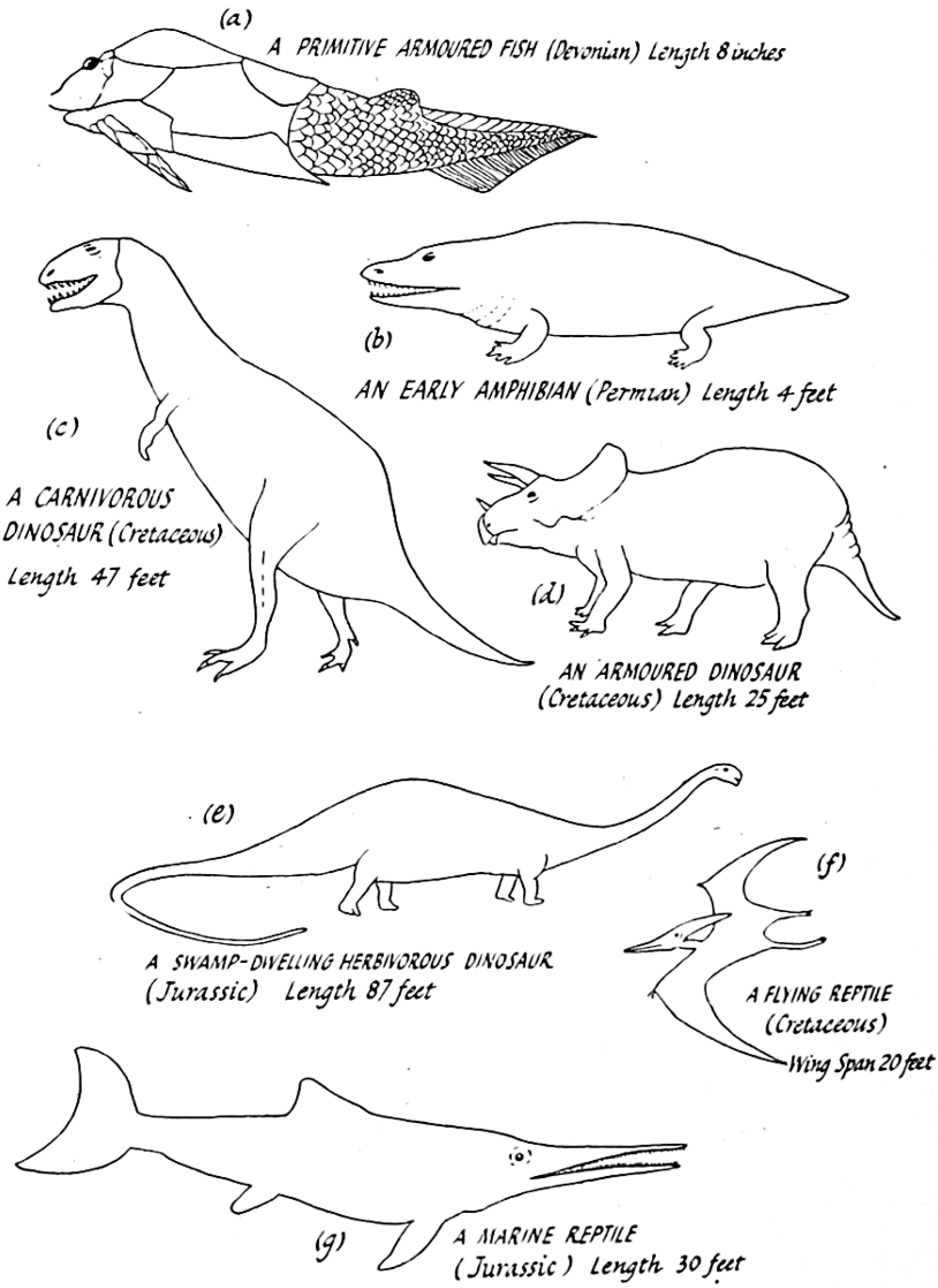


Fig. XVII, 8.—Some Extinct Vertebrates

(N.B. not drawn to same scale.)

(a) After Watson, (b) after Williston, (c), (d) and (e) after Lull, (f) and (g) after Swinnerton.

Ginkgoales, again dominant in the Mesozoic Era. They had many branches with numerous simple leaves, which in the modern 'maidenhair tree' or *Ginkgo* resemble in shape the maidenhair fern.

4. *Angiosperms* (covered seeds). The dominant plants of today with their seeds protected by a hard case. Very varied in character, as they include Grasses, Oaks, most Flowering Plants, etc.

The Changing Life of the Past

Calcareous algae and the trails of worms are the only undoubted forms of life which have been found in the *Pre-Cambrian* strata, yet a rich and varied fauna has been obtained from the overlying Cambrian beds, including advanced forms like the trilobites. The Cambrian fauna cannot have appeared suddenly, but must have evolved from a long series of ancestors. If these ancestors were soft-bodied, one can understand why they have not been found as yet. But this does not explain why so many forms of life began to secrete hard parts more or less simultaneously. It has been suggested that the chemical composition of the Pre-Cambrian oceans was different from that of subsequent times and that the waters did not contain the salts needed for the formation of hard structures.

Certainly calcareous rocks are much rarer amongst Pre-Cambrian than among later strata, but most of the Cambrian fauna used chitin, with some calcium phosphate, rather than calcium carbonate for their skeletons. The problem of the origin of the Cambrian fauna is bound up with a much greater mystery, the origin of Life itself. As yet, we have no convincing answer to this great riddle.

The common fossils found in the *Cambrian* rocks are inarticulate brachiopods and trilobites, whilst in the highest beds appear the first 'dendroid' or many-branched graptolites. At Mount Stephen in the Rocky Mountains are shales containing the remains of many soft-bodied creatures, including a number of worms and jellyfish, proving that the fossils found elsewhere in the Cambrian strata give but an incomplete picture of the life of the period.

In *Ordovician* times, forms with calcareous skeletons were more common. The articulate brachiopods appeared and, more rarely, corals and crinoids. Trilobites and graptolites were still the dominant groups, the true graptolites evolving from the dendroids. In the lower beds of the Ordovician System the graptolites had reduced their stipes to two in number; the stipes were uniserial, with the thecae on one side only. In the higher beds, the thecae were arranged biserially on either side of a single stipe (Fig. XVII, 6).

In the *Silurian* strata calcareous fossils, brachiopods, corals and

crinoids occur for the first time, in sufficient numbers to form thick beds of limestone. Mollusca are slightly more important than in the preceding systems, whilst the true graptolites, now represented by uniserial one-stiped forms, became extinct before the end of the Silurian Period.

There were great advances during the *Devonian* Period. Not amongst the invertebrates, for except for the appearance of the goniatites, there were no major changes from those found in the Silurian strata. Vertebrates, however, became common. Jaw structures of probably very primitive fish have been found in the Ordovician rocks of America, but it is in the non-marine Devonian beds of many parts of the World that we find, for the first time, abundant remains of fish. In the lower beds they are long extinct and primitive sluggish forms (Fig. XVII, 7), but in the higher Devonian strata appear the first of the true fish. In pre-Devonian times plant life seems to have been restricted to marine algae, the first primitive land plants being found in Devonian rocks. Before the end of the Period, a large number of pteridophytes had appeared.

During the *Carboniferous* Period certain kinds of fish began to crawl out on to the mudflats and develop into Amphibia. The luxuriant vegetation that is now compacted into coal was very similar to that of late Devonian times. Amongst the invertebrates, trilobites were on the decline and only just survived into the Permian Period, crinoids were at their acme, whilst many new forms of corals and articulate brachiopods appeared and mollusca continued their slow rise in importance.

The Armorican Orogeny produced great geographical changes; the succeeding Permian and Triassic strata being mostly of continental origin, but where marine strata are found, those of *Permian* age contain a fauna of Palaeozoic character, whilst those of *Triassic* age yield the forerunners of the forms that dominated the Mesozoic seas. This was a period of great development on land. Amphibia (Fig. XVII, 7) were numerous and varied, and from some of them developed the reptiles and, from the mammal-like reptiles, the first very primitive mammals. There were marked floral changes as well; the predominant pteridophytes of the Carboniferous forests giving place slowly to gymnosperms, especially the cycads and the ginkgos.

The invertebrates of the marine *Jurassic* and *Cretaceous* strata are very different from those found in the Palaeozoic rocks. Rugose and tabulate corals have been replaced by the hexacorals, crinoids are much less important and include a number of nektonic forms, the rare Palaeozoic regular echinoids have given rise to many different

kinds of irregular echinoids, brachiopods become less important and consist of a limited range of Articulata, whilst the Mollusca made a great advance in importance. Not only are the gastropods and the lamellibranchs much more numerous and varied, but it was then that ammonites and belemnites reached their heyday. It was also the 'Age of Reptiles'; flying forms with a wing span of up to 30 feet gliding over the seas, in which swam other reptiles, 30–40 feet in length, perfectly adapted to chase the fish of modern type. On land roamed the *Dinosaurs*, the herbivorous forms of the most bizarre shape and up to nearly 100 feet in length and 40 tons in weight (Fig. XVII, 7), being preyed upon by the largest carnivores that ever walked the Earth. From certain dinosaurs evolved the birds, but like the contemporary mammals, they were a very insignificant part of the fauna. There were changes, but slower changes, in the plant world as well. The first angiosperms appeared during the late Jurassic Period, but it was not until Tertiary times that they became dominant and grasslands extensive.

The close of the Mesozoic Era brought great changes amongst both invertebrates and vertebrates. Ammonites, belemnites and the great reptiles all became extinct. Why we do not know. It has been suggested that disease may have wiped out the mighty dinosaurs, but it is unlikely that this can be proved from the study of the hard parts alone. Gastropods and lamellibranchs swarmed in the *Tertiary* seas, whilst in the warmer seas of the Tethyan belt hexacorals, irregular echinoids and the giant Foraminifera were extremely abundant and formed great thicknesses of limestone. Mammals took the place of the reptiles. The Eocene and Oligocene strata have yielded many types of primitive mammals, usually with small brains, but these soon became extinct. In the same rocks are found ancestral, often very small, forms of the larger brained modern mammals, who developed rapidly during upper Tertiary times. Amongst these were the Primates, the oldest known ape having been found in the Oligocene rocks of Egypt.

From these Lower Tertiary Primates evolved, on the one hand, modern apes and monkeys, and on the other hand, *Man*. As one would expect fossil remains of early man are regrettably few, despite the fact that his habit of sheltering in caves meant that his remains had a better chance of being preserved than those of creatures which merely roamed the land surface. It was in cave breccias of probably late Tertiary date that the late Dr. Broom discovered in South Africa, the skulls and limb bones of creatures showing a combination of human and apelike features. But if the actual remains of man are

few, he fortunately left traces of his presence in his implements, usually fashioned out of most durable rocks, like flint and obsidian. Throughout the *Pleistocene* strata we can trace the growth of man's technique in working stone. In the lowest beds we find extremely crude implements, little more than stones, which he had picked up, because their shape was suitable for some purpose. But soon he developed the art of shaping flint by striking flakes off it and by Upper Pleistocene times he was producing the most beautifully shaped and finished arrow heads and was also carving bone. During the *Holocene* Period Neolithic man learnt to work metals.

The Use of Fossils

In an earlier section (p. 16) we referred, in general terms, to the use of fossils as time indices. We are now in a position to discuss this important point more fully. Just as organisms are divided into groups, commencing with phyla and ranging into smaller units, so the series and systems of rocks can be subdivided. The name *Zone* is given to a group of strata, perhaps only a few feet or even inches in thickness, to which certain genera or species of fossils are restricted. A zone must therefore be composed of rocks which were deposited during a limited period of time and if a particular zone can be traced over a wide area, it is a valuable 'marker' horizon.

Not all groups of fossils are equally useful as *zonal indices*. The most suitable are the graptolites and ammonites, which were nektonic or planktonic and therefore were widely distributed during life. These groups also evolved rapidly, so that each genus or species had a restricted time range. Benthonic forms such as the brachiopods are much less suitable, for they usually evolved more slowly and also could only be distributed during their brief larval planktonic stage. Even then the larvae would only develop if they happened to settle at the correct depth on the right type of sea bottom. Therefore the distribution of benthonic forms is controlled by the conditions of the sea floor, which vary much more than do those of the upper parts of the oceans. Nektonic and planktonic forms, also, sink down to the sea floor after death, but in the case of very buoyant forms this may take a long time, during which the organism may be dispersed far beyond its living area by currents. For example the shells of certain floating gastropods, which live only in the seas around Japan, are sometimes washed up on our own coasts.

The strength of the shell of an organism will also affect its distribution in rocks. Ammonites with strong calcareous shells are

found in shales, limestones and even arenaceous strata, but the more fragile graptolites usually occur only in argillaceous beds. Graptolites must have drifted into areas where sands were being deposited, but their skeletons were broken up, before they could be preserved by wave and current action.

Some systems can be zoned with greater precision than others. The rocks of the Ordovician and Silurian Systems have been subdivided into numerous zones, based on the distribution of graptolites, but the marine Devonian and Carboniferous strata of England contain very few pelagic fossils, for the goniatites, which would have been ideal, are unfortunately rare. We therefore have to use brachiopods and corals, which not only evolved slowly, so that the individual zones are thick, but they are also, to a considerable extent, facies fossils. *Facies* is the term applied to rocks deposited under certain conditions, which have determined both their lithology and their faunal content. A reef is an example of a facies, for reef limestones have distinctive lithological characters, whilst a particular assemblage inhabits a reef. It therefore follows that similar facies faunas found in different areas may not necessarily be contemporaneous, for the faunas could only flourish when conditions were suitable, and it may have taken time for these conditions to spread from one area to another. We can only correlate facies faunas successfully, if amongst them are some forms with a restricted time range, but these may not always be present.

The majority of the Jurassic and parts of the Cretaceous systems are zoned very successfully by ammonites, but these become rare in the Chalk and benthonic forms like brachiopods and echinoids have to be used in rather thick zones, though the widespread distribution of certain nektonic crinoids fortunately provides us with some thinner zones. In the English Tertiary beds, Foraminifera, which are excellent zone fossils in the Tethyan regions, are unfortunately rare and only occur at a few horizons; the lamellibranchs and gastropods, which have to be used, are by no means ideal zonal indices.

Another possibility that has to be considered is that the fossils collected from a bed may not all be *indigenous* forms, that is, forms that were living when the bed was being deposited, but may include fossils *derived* from the erosion of older beds. Often there is a difference in preservation, the shells of the contemporary fossils being calcareous, whilst the derived fossils were phosphatized, whilst they were lying unburied on the sea floor. The age of a bed is therefore determined by the youngest shells which it contains. On the other hand, the presence of derived fossils does give us evidence of the

rocks that were undergoing erosion at a particular time and also shows that the beds containing them must have been deposited very slowly.

This is an example of another use of fossils. They not only date the beds, but in the case of facies faunas, give us valuable evidence as to the conditions under which the beds were formed. (Fossils are therefore of the greatest value to geologists in helping them to divide the succession of rocks of an area into units which can be mapped.) In particular a number of zones may be recognizable in a considerable thickness of beds of similar lithology, which cannot otherwise be subdivided. It is from his map that the geologist deduces the structure and geological history of the area and clearly the thinner the subdivisions mapped, the more precise will be our knowledge of the relationships of the beds. The most difficult sedimentary rocks to interpret are usually those laid down on land, for they are generally unfossiliferous. Variations in lithology can be mapped, but the geologist suspects that over a big enough area the lithological units will be *diachronous*, that is, will not always be of the same age. In the deserts of today we can see sand dunes forming in one place and elsewhere pebble fans or saline deposits. We know from the excavation of the buried cities of central Asia that only a slight change of climate is needed in marginal areas for sand dunes to spread across areas that were previously fertile. Archaeological evidence enables us to date the time at which each city was overwhelmed by the advancing sand. The dates are not the same and therefore these sand dunes of, geologically speaking, very recent formation are not all of the same age, for the base of the sand deposits rests on different archaeological time planes in the different cities. Such horizontal movement of the facies belts of continental deposits must have occurred to a considerably greater extent during the much longer periods of the geological past, but without fossils to take the place of the coins, potsherds, etc., on which the archaeologist bases his dating, we are often unable to prove that fossil continental deposits are diachronous or to be sure that the evaporite deposits of one area are strictly contemporaneous with the fossil sand dunes of somewhere close at hand.

With fossiliferous deposits, particularly those which can be divided into fairly thin units, our picture of the palaeogeography of the past is much more precise. Each species used for zoning must, however, have needed time to spread from the place where it first developed to the whole of the area subsequently occupied by the species. This time of migration is, however, usually regarded as but

a fraction of the period of existence of a species and therefore whilst there must always be some element of diachronous relationship between fossiliferous strata it is held to be small. The deposits yielding a good zonal index, such as an ammonite or a graptolite, are held to have been laid down during the same period of geological time and to be approximately contemporaneous.

Fossils therefore enable time planes and 'marker horizons' to be traced through the sedimentary rocks and these may be of great economic importance. Many geologists are employed as palaeontologists by the oil companies, studying the fossils obtained from surface exposures and borings, so that the rocks can be dated as precisely as possible and their detailed structure elucidated. There are many other problems of economic as well as academic geology to whose solution the study of fossils gives invaluable aid.

Finally Palaeontology provides the major part of the evidence for the reality of *Evolution.* Linnaeus (1707–1778) regarded his species as clean-cut units, which had been created and then had persisted unchanged. He could not picture any intermediate stages between species. Later workers, notably Lamarck (1774–1829), suggested that species could develop from other species, but were unable to support their theories convincingly. In 1859 Charles Darwin published his immortal *Origin of Species* and proved by a wealth of detail, much of which was palaeontological, that species were not rigid entities, but changed with the evolution of new species. The subsequent and still continuing arguments amongst scientists about Evolution are concerned with the manner by which Evolution takes place.

A brief account of the development of the main groups of organisms has been given on pp. 248–252. Let us now consider a few selected examples in detail, to see what evidence they give as to the manner and cause of evolutionary change.

Sufficient remains have been collected, mainly from North America, for the evolution of the *horse* to be known in fair detail. The earliest known horses, from rocks of Eocene age, were about the size of a fox terrier and had four toes on the front and three on the hind feet. All these toes touched the ground. As the climate of the Eocene times was warm and moist and these primitive horses lived mainly in marshy swamps, a rather spreading foot must have been an asset. But in Oligocene times the climate began to become drier and the marshes give place to woods and grassland. The horses found in the Oligocene rocks are bigger, up to the size of a modern sheep, and whilst they had three toes on both hind and fore feet, the middle

toes were larger than the side toes and bore most of the weight of the animal. The climate continued to become more arid and animals had to travel greater distances to find sufficient grass for sustenance. The horses from the later Tertiary strata show a steady increase in size and whilst three-toed, the side toes often did not touch the ground, and the low-crowned and rather soft teeth of the early Tertiary horse had evolved into deep-crowned teeth with complex folds of hard enamel, which would not be ground down too quickly by the tougher grasses that had replaced as food the softer swamp plants. Finally in late Pliocene times the modern types of horse appeared, running on one toe on each foot, with mere traces of the side toes forming the splint bones, whilst the teeth had become still deeper and more complex.

This evolutionary series (Fig. XVII, 9) shows the gradual change from a rather generalized form to one adapted very perfectly to a special kind of environment, the steppe land of central Asia and the prairies of North America.

The evolution of the horse spans a period of nearly 60 million years, but particularly in the older Tertiary rocks the remains of the earlier horses are very few and far between. Those that have been found are merely points on an evolutionary chain; points so widely spaced that whilst the general changes are clear, we cannot demonstrate the development of new species or even genera.

To do this we must study the less spectacular invertebrates, occurring in great numbers at certain horizons. For example, the rugose coral *Zaphrentis* is very abundant in certain limestone bands of the Lower Carboniferous rocks of Scotland. Carruthers divided the collections made from each horizon into a number of species groups, based on the length and arrangement of the septa, but many individuals showed characters more or less intermediate between those regarded as typical of a species group and it was difficult to decide with which group they should be placed. A comparison of the percentages of the different species groups found in the successive limestone bands shows that these corals were evolving, but that the path followed (Fig. XVII, 9) should be represented by a broad band (covering the range of species variation to be found at any one time) rather than by a line joining a number of distinctive forms as has been done in the case of the fossil horses, of which insufficient specimens have been found for their species variation to be adequately known.

This emphasizes one inevitable defect of the study of palaeontological material. The record, owing to the chances of preservation and collection described earlier, must be incomplete and there is always

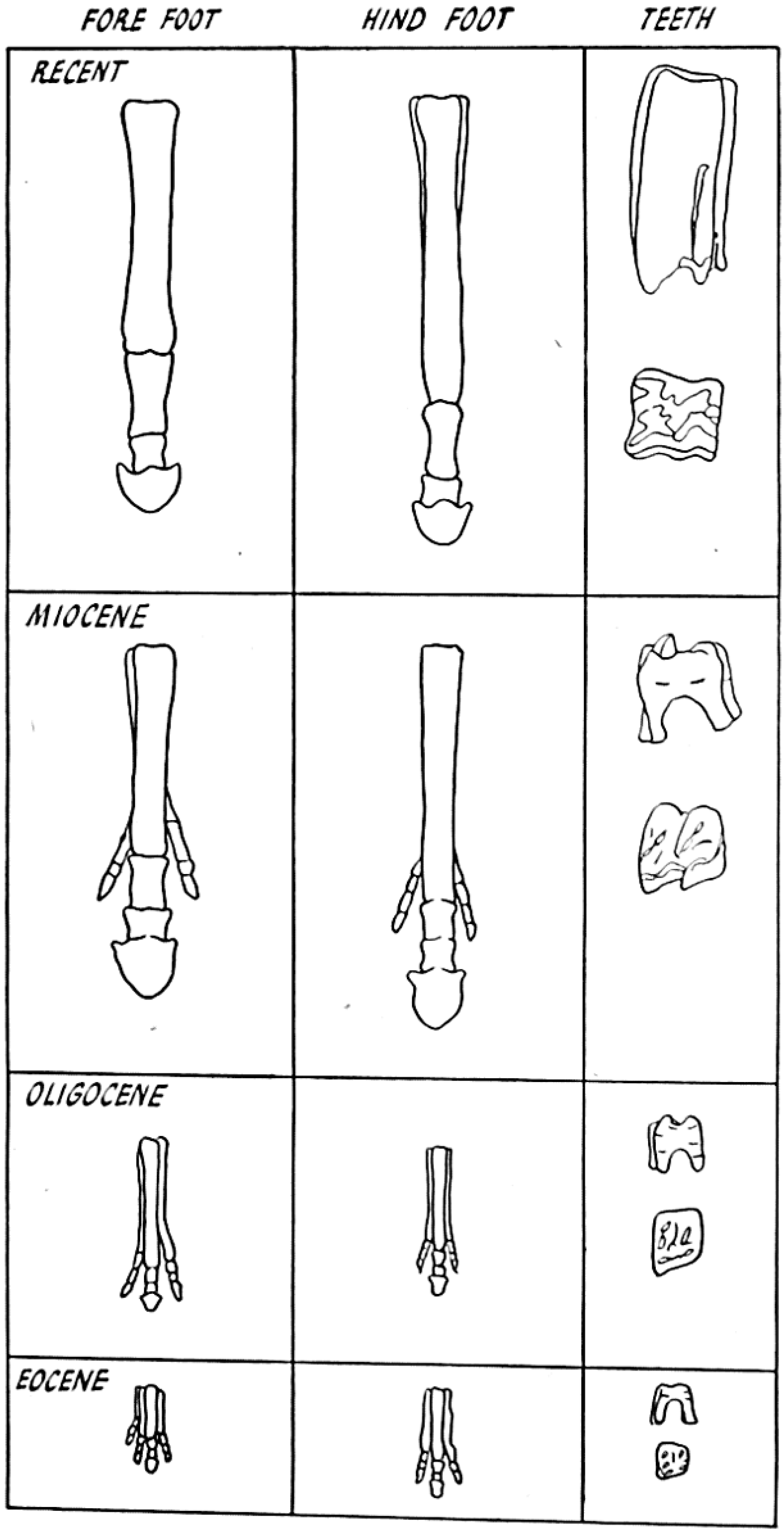


Fig. XVII, 9.—EVOLUTION OF THE HORSE
(After Roemer and Osborn.)

the danger of making erroneous assumptions of relationship in attempting to construct evolutionary sequences from incomplete material.

When large numbers of specimens can be collected from a thin band, as for example from one of the 'mussel bands' of the Coal Measures, which yield closely packed specimens of certain lamellibranchs, then it is possible to study a fossil population. If sufficient shells are measured and ratios such as length to breadth, etc., calculated, we can study the statistical variation of a particular species group. We find that the specimens from any one mussel band show a variation about a mean, just as one can see slight differences in any group of human beings (all members of the species group *Homo sapiens*) or a multiple tailor, for example, by the statistical analysis of measurements of a large number of people, can calculate the mean (the most commonly occurring) waist measurements, arm lengths, etc., on which to base his 'stock sizes'.

Such statistical work on the mussel populations of successive horizons has shown changes in the position of the means of species groups, similar to those described for the zaphrentids. The species merge into one another and therefore, with sufficient material, the limits of the species groups must be defined arbitrarily. On p. 236 one of the criteria given for a species, was that the members of it should be capable of interbreeding. With living material this can be tested and such species are described as *biological* species. The pedigree dog owner knows only too well that any two members of the species *Canis familarius* can interbreed. But the palaeontologist cannot apply this test and his species must be *morphological*, based on the presence of certain combinations of skeletal features. He can only suspect from the presence of intermediate forms that his species are also biological. If interbreeding can take place, then just as in human beings and dogs, each individual must inherit certain characteristics from his parents, grandparents, etc. We can therefore regard lines of descent as *lineages*, composed of a large number of interrelated individuals, showing in the course of time a gradual change in a definite direction.

The real problem is the cause of this change. In the very generalized story of the horses, it was suggested that the environment in which they lived was slowly changing its character. According to one school of thought, a species is capable of an infinite number of variations, but only those forms which are best adapted to the environment will give rise to the greatest number of descendants so that those variations which tend to confer more complete adaptation

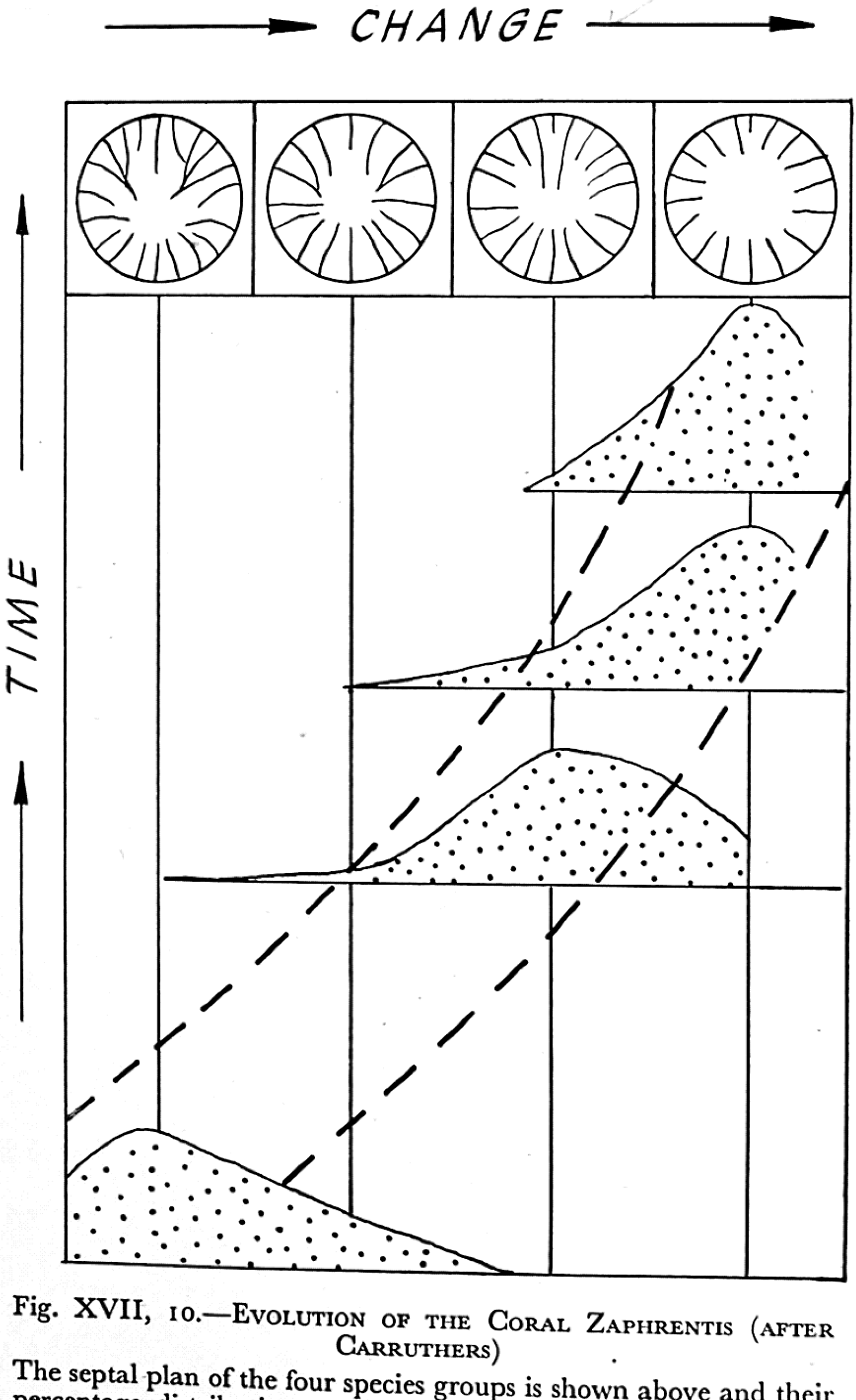


Fig. XVII, 10.—Evolution of the Coral Zaphrentis (after Carruthers)

The septal plan of the four species groups is shown above and their percentage distribution at different levels by the curves. Broken lines mark the direction of evolutionary change.

will gradually spread through the population, and therefore the environment has a predominant effect in moulding the path of evolutionary changes. A contrary view is that organisms evolve, owing to some internal urge, which is inherited and makes them change their shape, during the generations, by the excessive development of certain features and the suppression of others. An intermediate position is that inherited changes do occur and that the path followed is moulded, though not too rigidly, by the environment, and it is only those forms which are greatly out of adjustment with the environment that do not have descendants.

The great difficulty in dealing with fossil material is in assessing the evidence for environmental change, particularly in beds yielding large populations of invertebrates. With our present knowledge we can only reconstruct in very broad outline the conditions of the sea floors, delta swamps, etc., of the past. Slight, but doubtless very significant, changes of temperature, salinity of the water, etc., cannot be proved. Again the effects of disease in wiping out whole populations are unlikely to be demonstrable from the study of the hard parts of organisms. Environment must have played its part in moulding the evolutionary paths followed by lineages, but whether it was a predominant or only a relatively minor factor, cannot be assessed from fossil material alone.

CHAPTER XVIII

Brief Geological History of the British Isles

THE economy of the British Isles would have been very different if they had formed one of the Pre-Cambrian shield areas. The greater part of the World's mineral wealth occurs in the Pre-Cambrian rocks. Eastern Canada is a typical Pre-Cambrian shield and its mineral wealth is being actively investigated and exploited. But unfortunately the Pre-Cambrian beds of the British Isles are usually hidden under a great pile of later rocks and even where they do reach the surface, they are almost barren of minerals.

The Pre-Cambrian rocks can be divided into three main types, Archaean rocks, the so-called *Basement* or *Fundamental Complex*, consisting of gneiss and schist, so intensely metamorphosed that it is often very difficult to be sure whether they were originally sediments or igneous rocks, are exposed in the extreme north-west of Scotland, in Anglesey, in the Malvern Hills and at a few other places. In Scotland they are overlain with strong unconformity by the Algonkian, unmetamorphosed sediments, probably laid down under continental conditions. Beds of the same character are exposed in the Longmynd, a moorland area to the west of Church Stretton in Shropshire. Here the sediments are seen to pass downwards into a great succession of acid volcanic rocks, which must underlie much of the Midlands, for pebbles of them are widely distributed in later rocks. But whilst we can recognize these three main types of Pre-Cambrian rocks, their outcrops are too small and too widely separated for the history of the Pre-Cambrian Era in Britain to be reconstructed.

The Transgression of the Cambrian Seas

Wherever the junction between the Pre-Cambrian and the Cambrian strata is exposed, as in north-west Scotland, in Shropshire, near Nuneaton and in the Malvern Hills, it is clearly unconformable. The lowest Cambrian bed is a basal conglomerate containing pebbles of Pre-Cambrian rocks. The conglomerate passes upwards into sands, now compacted to quartzites, and these grade upwards into shales. Fossils are found at intervals and they are always marine forms. Therefore the Cambrian history of Britain must have commenced with a *marine transgression*, the sea spreading across an eroded surface of Pre-Cambrian rocks. The upward change, at many localities, from coarse-grained rocks to shales, is due to the deepening of the sea as the transgression continued. The highest Cambrian strata, however, become somewhat coarser in grade, showing that there was then a period of shallowing due to the retreat or regression of the sea. Unfortunately the evidence is too scanty to enable us to reconstruct the limits of the Cambrian seas. It is only in the extreme north-west of Scotland that we have clear evidence of the nearness of a shore line, for there the basal arenaceous Cambrian rocks are overlain not by shales, but by a rather unusual limestone, the Durness Limestone, which must have been deposited in a shelf sea.

The Lower Palaeozoic Geosyncline

With the development of the Lower Palaeozoic geosyncline, in early Ordovician times, the distribution of land and sea becomes clear. Along a belt striking north-east to south-west from the eastern part of the Southern Uplands of Scotland through the Lake District into north and central Wales, the Ordovician strata consist almost entirely of shales containing graptolites. These beds, the 'graptolitic facies', were laid down well away from land in the central part of the geosyncline. In some of the deepest-cut valleys of the Pennines and in Shropshire, the shales pass laterally into the 'sandy facies' consisting of a variable succession of sandstones, some calcareous, and siltstones, yielding a fauna of trilobites, brachiopods and other benthonic forms. Occasional shale bands occur and in them are to be found graptolites, which are of great value, as they allow the trilobite-brachiopod successions to be correlated with the uninterrupted sequence of graptolites found in the true geosynclinal belt. The sandy facies, with its numerous minor unconformities and other breaks in deposition, was clearly laid down in shallow water. Around Girvan, in Ayrshire, and in Anglesey, the sandy facies is

Fig. XVIII, 1.—The Lower Palaeozoic Geosyncline
The outcrops of rocks of Ordovician age are stippled. Their facies is shown by G for graptolitic, S for shelly and V for the main areas of volcanic rocks.

again developed, but here the beds pass south-eastwards into the graptolitic shales, proving that the north-western coast line cannot have been far distant.

The same general setting (Fig. XVIII, 1) continued into the Silurian Period, but there is a change in the character of the littoral facies. In Shropshire and Herefordshire there are several important limestones producing prominent scarps, such as Wenlock Edge. The basal and least persistent limestone, the Woolhope Limestone, is composed mainly of corals and calcareous algae; the overlying Wenlock Limestone is in its lower beds a fossil coral reef and in its higher beds a crinoidal limestone; whilst the highest limestone, the Aymestry Limestone, is locally composed of the tightly packed shells of brachiopods.

There is, however, one great change between the Ordovician and the Silurian rocks: vulcanicity was widespread during Ordovician times. Sometimes the lavas were poured out on the sea floor to form sheets of pillow lava, but more often the magma was viscous and acidic, building up volcanic cones, some of which probably formed volcanic islands. Not all the magma was ejected, for sills are quite common, whilst mineralization also occurred. The goldbearing veins of North Wales and the lead-zinc mines of Shropshire, worked by the Romans, but scarcely worth attention today, are the result of this Ordovician phase of vulcanicity. Igneous activity ceased in early Silurian times. The differences in hardness between the volcanic rocks and the shales have been etched out by subsequent erosion. Much of the finest mountain scenery in Wales (Snowdon, Cader Idris, etc.) and of the Lake District (Langdale Pikes, etc.) is carved out of the resistant ashes, agglomerates and rhyolitic lava flows of Ordovician date. In the Lleyn Peninsula, the sediments form almost flat country thickly plastered with boulder clay, above which rise steeply hills, such as the Rivals, marking the outcrop of the igneous rocks.

Towards the end of Silurian times changes occurred. The central part of the geosyncline was filled, not with shales but with a great thickness of ill-graded conglomerates, grits and sandstones of the greywacke facies. Uplift and rapid erosion must have occurred on the landmass to the north to produce this great southward spread of coarse detritus. In Shropshire, which is beyond the limit of the greywackes, the change is of a different nature, not so much in lithology as in faunal content. The rich and varied fauna of the limestones died out and in the highest Silurian rocks the bedding planes are covered with only three species of brachiopods. This must

mean a change in conditions, the seas having become brackish and only a few forms being able to endure the decrease in salinity.

The Caledonian Orogeny

These are all indications that the history of the geosyncline was drawing to a close. A thickness of nearly seven miles of sediments had been laid down in its deepest parts and now this great pile was to be folded and uplifted to form a mountain range.

The effects of the Caledonian orogeny are most pronounced in Scotland. There, along a great thrust belt traceable for 120 miles from Cape Wrath to Skye, Pre-Cambrian and later rocks have been thrust for many miles north-westwards over Cambrian, Algonkian and Archaean strata. To the south-east of this thrust belt the rocks have been intensely sheared and folded and, in addition to the dynamic metamorphism, they have been intruded by great masses of granite and other plutonic rocks, each of which has its metamorphic aureole. In the Southern Uplands of Scotland, the Ordovician and Silurian rocks have been thrown into tightly packed isoclinal folds, the complexities of which could not be unravelled until the sequence of the graptolite zones had been worked out. The beds are somewhat cleaved, but otherwise not metamorphosed, except in the aureole of the granite bosses, such as that of Criffel near Dumfries. The Criffel granite cuts Silurian strata and pebbles from it are found in the basal Carboniferous rocks, so that it must have been emplaced in late Silurian or Devonian times.

The same type of folding, with igneous intrusions, also affected the Lake District and here many of the finer-grained ash bands have been cleaved and converted into poor quality roofing slates. In Wales the folding is less intense, except in the famous Welsh slate belt, where fine-grained muds of Cambrian age have been so compressed between the Ordovician volcanic rocks of Snowdonia and masses of hard Pre-Cambrian rocks to the north, that they have developed a perfect cleavage. As one moves south-eastwards across Wales, the folding becomes of a more open character, until in Shropshire the Silurian rocks are unaffected by cleavage and dip at gentle angles.

The Old Red Sandstone

The Caledonian earthstorm profoundly changed the geography of Britain. The metamorphosed rocks of Scotland formed great mountain chains, which changed southwards through hilly country into a wide delta plain, covering what is now Shropshire and

Herefordshire. The deltas were built into the sea, but the position of the delta front varied considerably, at times advancing southwards into Exmoor, at other times being pushed back by the advancing sea into South Wales. The lines Thames–Severn marks approximately the northern margin of the Devonian seas.

To the south of this line, the marine Devonian rocks consist mainly of shales with massive limestones, containing numerous corals, as in the Torquay and Plymouth areas. Around Exmoor, the marine strata are intercalated with sandstones of continental origin. On the land area were laid down beds of very different lithology—the Old Red Sandstone—which is really a facies of the rocks of Devonian age. The Midland Valley of Scotland must have been a true intermontane basin, for there the Old Red Sandstone contains thick conglomerates and breccias, reddish sandstones often containing millet seed grains, and marls, and seams of salt and gypsum, which represent dried-up playa lakes. Interbedded with the sediments are great sheets of lava, forming, for example, the Sidlaw Hills, whilst cutting the sediments are numerous volcanic cones, etched out by subsequent erosion to form steep-sided hills, such as the one now crowned by Edinburgh Castle. This subaerial volcanic episode extended southwards to the Cheviots and northwards to Glencoe, but it did not reach the shores of the Moray Firth. Here and in the Orkneys are great thicknesses of fissile flagstones yielding abundant fish remains at several horizons. In Caithness these strongly jointed, almost flat-lying, flagstones have been attacked by the sea to form most spectacular coast scenery. On the delta plains of Shropshire and southern Wales, the Old Red Sandstone is of rather different type. Conglomerates and grits do occur, but in the main the beds consist of reddish marls with more resistant seams of current-bedded sandstone and nodular limestone.

The wearing down of the Caledonian mountain chains must have been nearly completed before the end of Devonian–Old Red Sandstone times, for the highest beds, in many areas, are mainly sands of aeolian origin, proving the presence of wide dune-covered plains.

The Transgression of the Lower Carboniferous Seas

In Lower Carboniferous times the sea transgressed northwards, reaching central Scotland at times, showing that the mountain chains had now been completely destroyed. In this sea was deposited the Carboniferous Limestone Series. But, as is often the case, this lithological term for a great thickness of beds is misleading. In the south the name is apt, for the beds are composed almost entirely of

limestone; a pale-coloured massively bedded variety, forming the cliffs of the Cheddar Gorge in the Mendips and of Dovedale in Derbyshire. In the Pennines, thick limestones are restricted to the lowest beds and are overlain by the *Yoredale facies*, consisting of a repetition of the following sequence: thin limestone—thick shale—thin sandstone, with perhaps a thin coal seam at the top, then another limestone and so on.

The topography of the Yorkshire Dales is due to the lithology of the gently eastward-dipping Yoredale Beds. The 'scars', to use their local name, mark the outcrop of the resistant sandstones and limestones, whilst the grassy slopes between are formed by the shales. The lithology of these beds also needs explanation. It is a good example of *rhythmic sedimentation*, the same rhythm being repeated many times over through hundreds of feet of strata, though the thickness of the individual members is constantly varying (Fig. XVIII, 2). The rhythm begins with a minor marine transgression during which the limestone with its corals and crinoids was laid down. As mud was brought into the area, limestone gave place to shales. Sedimentation was now taking place faster than subsidence and therefore the basin began to silt up, until finally sand flats were formed with forests growing over them, as is shown by the sandstones with their ganister tops and thin coal seams. Then occurred rapid subsidence, the sea swept in, killing off the trees, and a new rhythm began with the formation of the next limestone. These marine limestones are valuable 'marker horizons' and enable one to prove that the Yoredale facies is *diachronous*, that is, the conditions began earlier in the north than in the south and therefore the lower limit of the Yoredale facies is not everywhere contemporaneous, but cuts across the time planes.

We have dealt with these beds in some detail, for they are a good illustration of several principles of stratigraphy. Such a facies could obviously only have been deposited in an almost flat area, slight vertical movements of sea-level producing very considerable horizontal shifts of the shore line.

Northwards of the Pennines, beds of non-marine origin make up a greater proportion of the Lower Carboniferous succession, whilst the thick coal seams that are present in Northumberland and in the Midland Valley of Scotland must be due to long periods of emergence. The infrequent marine limestones do, however, prove that these areas were occasionally flooded by the sea. Vulcanicity still continued in southern and central Scotland, whilst the valuable Oil Shales (p. 200) of the Lothians were laid down in lagoons.

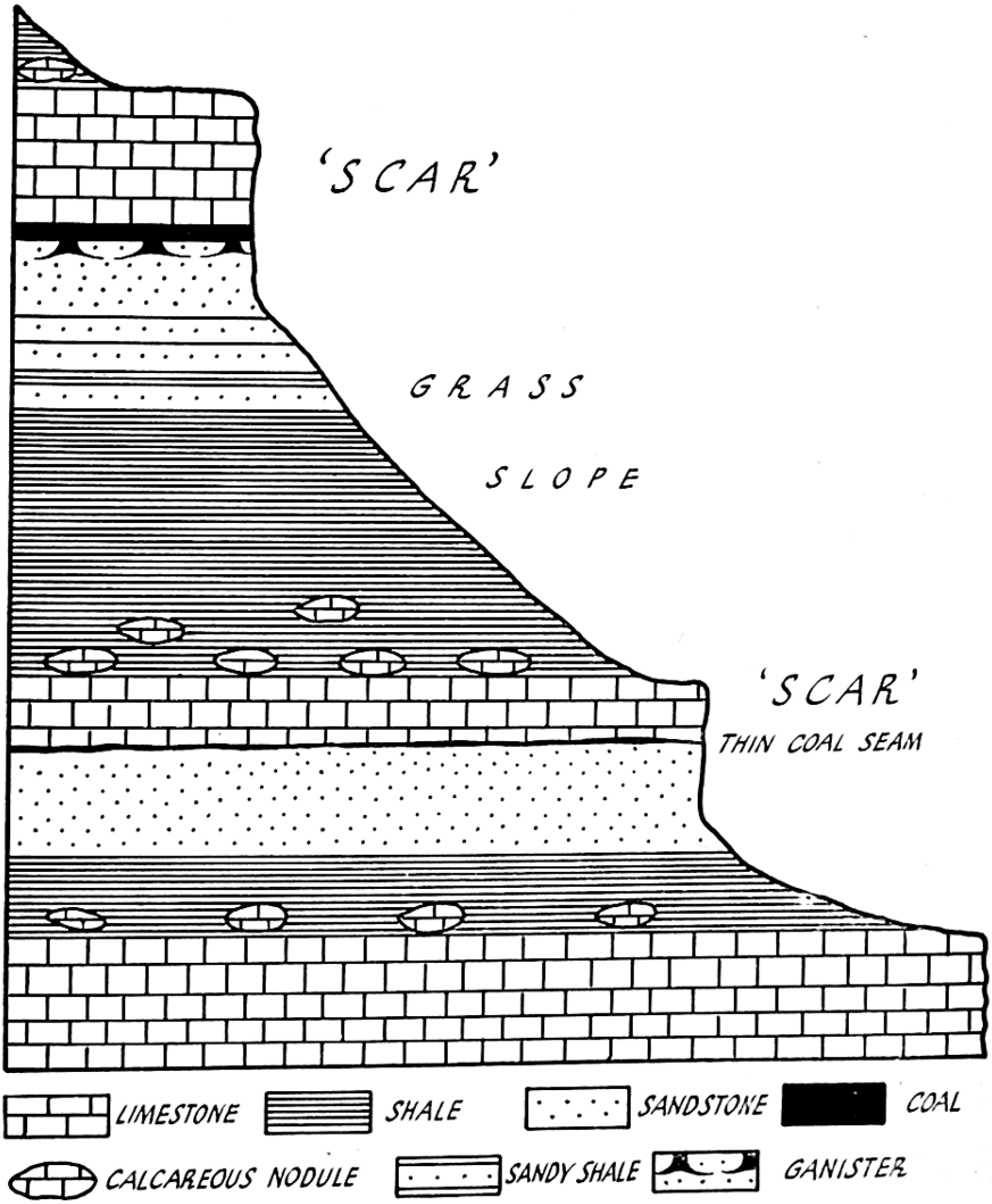


Fig. XVIII, 2.—Topographic Expression of the Rhythmically Bedded Yoredale Beds of the Yorkshire Dales

Note that each rhythm contains the same lithological types in the same order, but that thicknesses of the beds differ in the two complete rhythms shown.

The Millstone Grit Deltas

The basal beds of the Upper Carboniferous, the Millstone Grit, consist of massive grits and coarse sandstones, worked in the olden days for millstones, separated by thick beds of shale. The grits are often current-bedded and contain drifted plants, whilst the shales often yield marine fossils, including goniatites. These beds were laid down under conditions rather similar to those of the Yoredale facies, except for the periods of clear water necessary for the formation of limestones. Uplift, and therefore rejuvenation of drainage on the land area to the north, had produced a great supply of detritus and deltas were built by the rivers. The grits, in the main, are of subaerial origin, whilst the shales were laid down during the submergence of the delta front. The Millstone Grit is thickest around the southern end of the Pennines, where the barren grits produce the rather forbidding scenery of the Peak District.

The Coal Measure Swamps

The delta flats, in time, became a great area of swamps in which the Coal Measures were deposited. The basal beds show a rhythm of coal seam—thin shale with marine fossils—thick shale with fresh-water shells—sandstone—coal (Fig. XIII, 2), indicating that the sea still occasionally invaded the area, but the marine bands soon disappear and the higher beds are entirely of non-marine origin. The coal seams are sometimes interrupted by 'washouts', the coal being abruptly cut out by current-bedded sands, laid down in the channels of the distributaries flowing across the peaty swamps. The economic wealth of the Coal Measures is not restricted to coal. Ganisters or fireclays often underlie the seams, whilst the sandstones, like those of the Millstone Grit, are frequently good building stones. Unfortunately they soon darken on exposure and become smoke-grimed, hence the sombre appearance of many of the towns in the valleys of the Pennines. In Staffordshire and Scotland, the upper part of some of the coal seams contain nodules of Blackband Ironstone. The Upper Coal Measures are usually barren of coal but contain shales often suitable for high-grade bricks, whilst in the Potteries of Staffordshire are many good pottery clays.

Igneous activity persisted through Carboniferous times in central Scotland, but towards the end of the Period, sills and dykes were more common than lava flows. In England the igneous activity was much less extensive. The 'toadstones' of Derbyshire are basaltic flows and tuffs and sills in the Carboniferous Limestone, whilst in the Midlands some basaltic flows and sills are interbedded

with the Coal Measures. The red colour of the barren highest Coal Measures is usually thought to be due to the weathering of laterites and bauxites formed on the basaltic rocks of the higher ground, surrounding the swamps.

The Armorican Orogeny

The Lower Palaeozoic geosyncline lay right across the British Isles, but during Upper Palaeozoic times Britain formed the northern margin of a geosyncline extending across northern France and Belgium to the Rhineland. As a result the Armorican orogeny did not affect Britain so severely as did the Caledonian earthstorm. It is only in the extreme south-west that the Devonian and Carboniferous rocks were intensely folded, cut by thrusts, and intruded by the granite batholiths of Devon and Cornwall (Fig. X, 8). These granites were later heavily mineralized, copper and tin being the chief vein minerals (p. 122), whilst they were also attacked by hot gases with the production of much tourmaline and also, particularly in the St. Austell area, of deep pipes of china clay produced by the kaolinization of the feldspars. An important belt of thrusting extending through extreme South Wales to the north of the Mendip Hills marks the northern limit of the strongly folded area. To the north of this, the beds were folded only gently, but there was much block faulting, whilst in the Pennines the Whin Sill and its associated dykes were intruded.

The effects of these movements was that the great sheet of Coal Measures, covering originally the greater part of the British Isles, was flexured and faulted. Erosion soon began to strip the soft sediments of the upstanding areas. The coal fields of Britain were, therefore, blocked out soon after the Armorican orogeny. As regards their surface expression, one can recognize three types of coal fields, which are all essentially tectonic basins in structure. The South Wales coal field is a good example of a completely exposed coal field with now no cover of post-Carboniferous rocks, the Nottingham and Yorkshire field is a typical partially exposed field, whilst the East Kent field is completely hidden and was only proved when deep borings were made through the unconformable cover of Mesozoic rocks (Fig. XVIII, 3).

The New Red Sandstone Deserts

The Armorican Orogeny greatly changed the geography of Europe. A new geosyncline, the *Tethys*, was formed along the line of the Mediterranean. To the north of this was a land area. Just as the

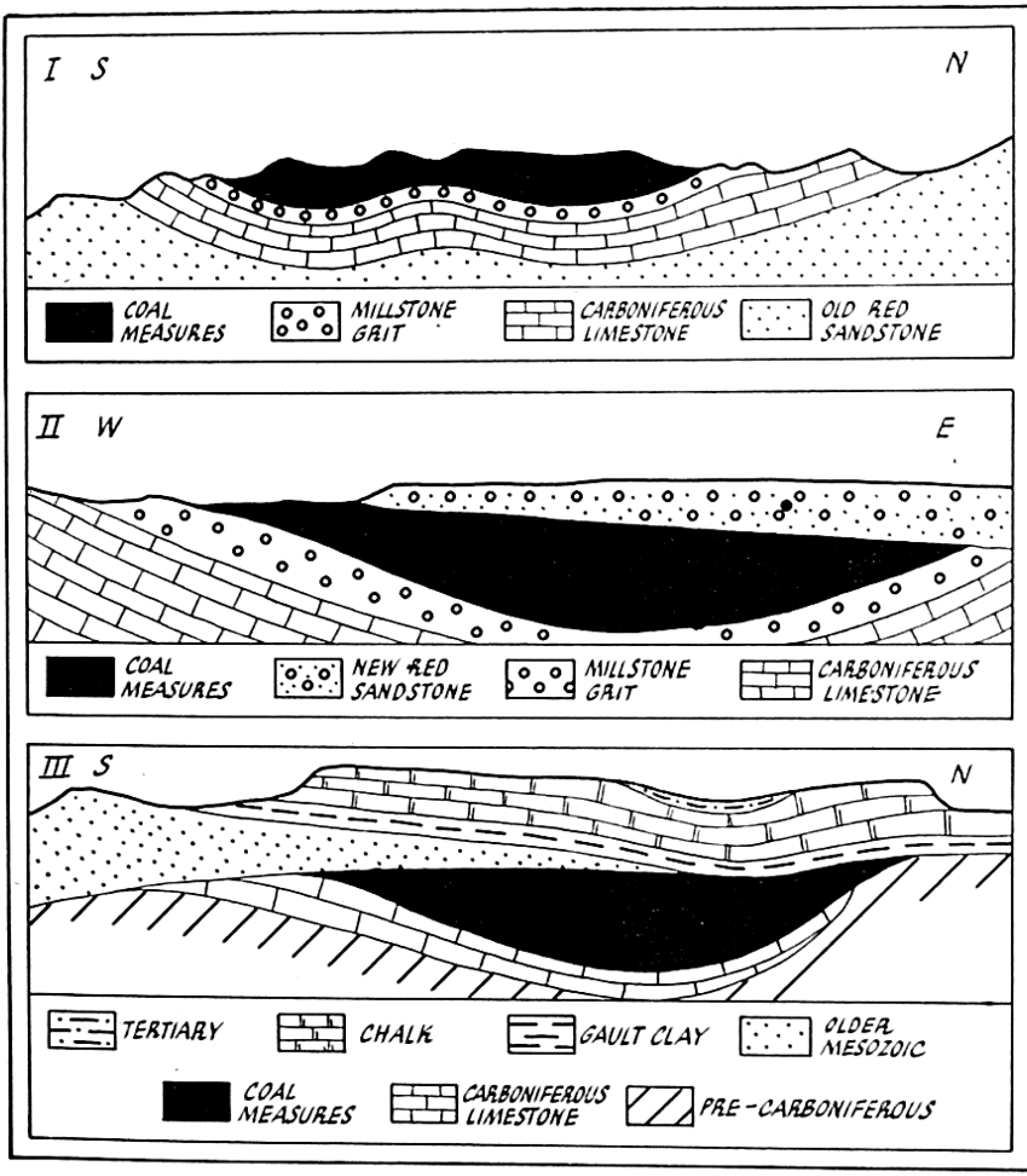


Fig. XVIII, 3.—TYPES OF COAL FIELDS

Sketch sections across.

I. A completely exposed coal field (South Wales).
II. A partially concealed coal field (South Notts).
III. A completely concealed coal field (East Kent).

Note in III the overstep of the Gault Clay northwards across older and older strata.

Old Red Sandstone was formed from the destruction of the Caledonian mountain chains, so the erosion of the Armorican chains, during the Permian and Triassic Periods, produced the New Red Sandstone. There is much similarity between the Old and the New Red Sandstone. Both contain breccias and conglomerates, especially in the basal beds, and these pass upwards into sands, which are often fossil sand dunes, the highest beds being mainly marls. But there are differences as well. In the first place volcanic rocks are almost absent from the New Red Sandstone. Secondly evaporites are much more common in the New than in the Old Red Sandstone. This is particularly the case in north-eastern England.

Early in the Permian Period an arm of the Tethys transgressed across Germany into northern England and north-eastern Ireland. In this sea was deposited the Magnesian Limestone with a typical marine fauna in its basal beds. The connection with the Tethys was, however, soon broken and as the waters became more saline, the marine fossils died out. Finally thick beds of anhydrite and salt were deposited and recently, deep borings in east Yorkshire have proved that the valuable deposits of potassium salts of northern Germany extend into England. In Triassic times another advance of the sea occurred, but this time it did not reach England, so that our Triassic beds are entirely continental in origin. They contain valuable deposits of salt in Cheshire and Staffordshire and of gypsum in Nottingham and elsewhere, laid down in playa lakes.

The Permian sea did not reach midland or southern England, and there the New Red Sandstone is entirely of continental origin. Whilst the New Red Sandstone of the British Isles is usually divided into Permian and Triassic portions, in the absence of fossils, particularly of marine fossils, it is impossible to be sure that these divisions are exactly equivalent to the Permian and Triassic beds of other parts of Europe. The highest beds of the New Red Sandstone are marls, largely fossil loess, showing that the Armorican chains had by then been completely worn down and that the British Isles must have been in large part reduced to a peneplain.

The Jurassic Cycle of Sedimentation

The Jurassic rocks tell the story of a third advance of the sea from the Tethys, an advance which submerged almost the whole of the British Isles; but towards the end of the period the sea retreated and the British Isles once again became a land area. Such a transgression followed by regression is called a *cycle of sedimentation*. Many systems span such a cycle. The Cambrian is one example, though

the regressive phase was not completed in Britain, being only represented by a shallowing of the sea. The Carboniferous System spans another cycle, but here, by contrast, the regressive phase is very prolonged, covering nearly the whole of Upper Carboniferous times.

The Jurassic cycle of sedimentation was not a simple one. The initial marine transgression was rapid. Owing to the low relief and softness of the higher Triassic rocks, the basal beds are not typical basal conglomerates, but shales and fine-grained limestones marked by the incoming of a marine fauna and including the *Rhaetic Bone Bed*, with its numerous remains of lungfish. The sea soon deepened. The Lower Jurassic rocks are mainly shales, with, at their base, the regular alternations of shale and thin limestone so well seen at Lyme Regis (Plate I). At Banbury in Oxfordshire and in the Cleveland Hills of Yorkshire, there are beds of sideritic iron ore.

Then followed a partial regression of the sea. In southern England, the Middle Jurassic strata are a variable succession of oolitic limestones, sands and even clays. Where the limestones are thick, they form the Cotswold Hills, rising above the strike vale of the Lower Jurassic shales. The characteristic Cotswold scenery with its stone-built towns and its stone walls is due to the numerous horizons of good building stones in the Oolites. In Northamptonshire these oolitic limestones pass into oolitic iron ores. But it is in Yorkshire that the nature of the Middle Jurassic rocks changes most completely. The beds are not marine limestones but shales and sandstones of deltaic origin, very similar in lithology to the Millstone Grit and in the moors behind Scarborough producing very similar scenery. During Middle Jurassic times, deltas must have spread southwards from a northern land mass into Yorkshire, whilst further south the sea was shallow and current-swept.

This was not the beginning of the close of the cycle, for a new transgression swept northwards across the delta flats with the sea spreading along both the east and the west coasts of Scotland. The Upper Jurassic rocks are thick beds of alternately clay and limestone. One of the clays, the Oxford Clay, is extensively worked for bricks (p. 184). The end of the Jurassic Period is marked by the final regression of the sea. The famous Portland Building Stone is an oolitic limestone laid down in a shallow sea which covered only southern England. It is overlain by non-marine strata, deposited mainly in freshwater lagoons, but fossil soils, such as the one which underlies the Fossil Forest of Lulworth Cove in Dorset, prove that there were periods of emergence.

The Cretaceous System

The Cretaceous System also spans a cycle of sedimentation, but in this case it is the transgressive phase which is unusually prolonged. At the beginning of the period, a northern sea covered eastern Yorkshire and parts of Lincolnshire, whilst south-east England and Wessex were part of the delta plain of rivers flowing towards the Tethys. The lithology of the beds deposited on this delta plain differs little from that of the highest Jurassic strata of the same area. A shallow sea spreading northwards from France submerged the delta flats and eventually extended north-westwards round a landmass in the London area to join with the northern sea. The beds deposited in this sea are known as the Lower Greensand; a rather misleading term for whilst they are often sandy, they are rarely green in colour, for the grains of glauconite which they contain have usually been weathered to shades of brown, red, etc. The transgression of the sea continued. The London landmass was finally submerged and on it was deposited the Gault Clay. To the west of London the Gault passes laterally into the Upper Greensand, which usually is green in colour. This bed was laid down in shallower water than the Gault and therefore whilst the two beds are contemporaneous, there is a considerable difference in their faunas, the Gault containing abundant ammonites, belemnites and thin-shelled lamellibranchs; the Upper Greensand sponges and thick-shelled lamellibranchs, especially oysters, but very few ammonites and belemnites. In Dorset and East Devon the Jurassic rocks and the New Red Sandstone were tilted eastwards and eroded before the Cretaceous sea reached the area, so that the Upper Greensand oversteps on to older and older strata.

The transgression of the Cretaceous seas still continued and at their maximum extent almost the whole of the British Isles must have been submerged, and a bed of rather unusual lithology, the Chalk, was deposited. The basal beds of the Chalk are a clayey limestone and they pass upwards into a soft white limestone of singular purity, often over 97 per cent $CaCO_3$. The Chalk differs from the Silurian or the Carboniferous limestones, for it is not composed mainly of corals, crinoids or brachiopods. Indeed fossils are often extremely difficult to find in it. Nor does it show like the Magnesium Limestone evidence of the evaporation of an enclosed sea. Except in its basal beds, its content of clastic material is small. The Chalk must therefore have been deposited in an open sea into which very little land-derived material was carried. The prolonged erosion throughout Mesozoic times, of the surrounding land areas

must have reduced them to peneplains across which flowed rivers carrying their load almost entirely in solution. The presence of millet seed sand grains in the littoral facies of the Chalk of Antrim and western Scotland suggests the presence of deserts on the land areas. The waters of the Chalk seas were warm and saturated with calcium carbonate; ideal conditions for the deposition of calcareous oozes, composed of the skeletons of very minute lime-secreting algae, but with few Forminifera, so that the Chalk cannot be compared with the foraminiferal oozes which are being formed today at depths of 1000 fathoms or more. The rare echinoids, lamellibranchs, etc., of the Chalk are not deep sea forms and it is unlikely that the depth of the Chalk sea greatly exceeded 200 fathoms.

This unusual limestone with its lines of flints, laid down under such special conditions, gives rise to very distinctive scenery. The Chalk downlands are characterized by few flowing streams but by numerous dry valleys (p. 64) whose sides form sweeping curves. Owing to its purity, Chalk produces a very thin soil with a specialized flora, mainly of creeping plants. Woodlands are only extensive, as in the Chiltern Hills, where the Chalk is capped by spreads of Clay-with-Flints, which contain much material derived from the erosion of a sheet of Tertiary beds.

The sub-Eocene Unconformity

Towards the end of the Cretaceous Period there was a great change in geography which was due not to great earth movement but to the final regression of the Mesozoic seas and the formation of a new basin of sedimentation around the southern end of the North Sea. The surrounding land areas were uplifted and eroded, so that in England there is scarcely any trace of the beds laid down during the regression of the Cretaceous seas.

The basal Tertiary beds everywhere rest on the Chalk with conformity, but there are several indications of a considerable break in deposition. There is the abrupt change in lithology from very pure limestone to coarse, even pebbly, sands. Then the sands contain numerous pebbles of flint, sometimes only slightly but more often very completely rounded. These flint pebbles show that a considerable thickness of Chalk must have been destroyed. The upper surface of the Chalk is often marked by worm borings infilled with Tertiary material. But if instead of examining a single section the highest beds of the Chalk are studied over a wide area, it is found that the Tertiary beds rest on differing zones of the Chalk. Clearly the Chalk must have been warped and eroded before the deposition of the

basal Eocene strata, but the warping was so slight that a difference in dip between the Cretaceous and Tertiary strata cannot be detected in an exposure.

Sedimentation and Vulcanicity in Early Tertiary Times

The Eocene beds of south-eastern England were deposited during several minor cycles of sedimentation. Rivers flowing from the higher ground of western Britain built deltas into the ancestor of the North Sea. The coast lines were constantly changing their position, according to whether delta formation or marine transgression was dominant. As a result, the Eocene sediments of the London and Hampshire basins vary rapidly in lithology, both vertically and horizontally. In the east they are mainly marine clays, often containing a rich and varied fauna of lamellibranchs and gastropods, but in the west they are composed mainly of sands, often current-bedded, and mottled clays. Fossils are few, though drifted plants are plentiful at a few localities. In the central parts of the two basins these two facies interdigitate in a rather complicated manner.

The Oligocene beds, which are present only in the Isle of Wight and the southern New Forest, were laid down almost entirely under non-marine conditions, for at the close of the Eocene Period the open sea moved far to the east and only its most extensive transgressions penetrated into southern England.

In north-east Ireland and western Scotland, the Chalk is overlain by very different rocks; sheet after sheet of basaltic lava produces a terraced topography, the central part of the flows forming crags, the more easily weathered pumaceous tops grassy slopes. The perfect polygonal jointing of some of the flows is seen to perfection at the Giant's Causeway in Antrim (Plate II) and in the island of Staffa. The presence, at intervals, between the flows of sediments, including laterites, bauxites and plant-bearing horizons, show that these lavas are subaerial. The deeply dissected volcanoes of Hawaiian type, from which this great pile of plateau basalts was extruded, can be studied in Mull, Skye, Arran and the Mourne Mountains of Ireland. After the extrusive phase followed tension and the opening of fissures trending north-west to south-east, which were filled by basaltic magma, to form the great dyke swarms of Mull and elsewhere.

Lavas of the same type are found in eastern Greenland, Iceland and Spitzbergen proving that in early Tertiary times, the whole North Atlantic region was one great igneous province. The volcanoes of the British Isles have long been extinct, but the numerous

geysers in Iceland indicate that activity has not completely ceased there. Indeed there was a considerable eruption from Hecla in 1947.

The Alpine Earthstorm

Only the furthest ripples of the Alpine earthstorm, caused by the folding of the Tethyan geosyncline in mid-Tertiary times, reached southern England. The Mesozoic and Lower Tertiary rocks of the London and Hampshire basins, the Wealden anticlinorium and Wessex were flexured into a large number of minor asymmetrical anticlines and synclines with a steeper northward than southern dip (Fig. IX, 3). It was only in the Isle of Wight and between Weymouth and Swanage in Dorset that the beds became vertical or were even slightly overturned, but there was no metamorphism.

More important than such slight structural complications was the uplifting of England to form a land area. A long period of erosion during the latter part of the Oligocene and the whole of the Miocene Periods ended in the cutting of a peneplain across the warped surface of the Chalk, whilst in the Wealden area erosion cut down into beds well beneath the Chalk.

The Last Invasion of the Sea

In early Pliocene times a sea transgressed from the east across this peneplained surface and submerged the area to the east of a line extending from the Chiltern Hills to Marlborough and Weymouth. A veneer of sand and shingle was spread by the Pliocene sea across the folded Cretaceous rocks. Uplift in the south caused the sea to retreat towards East Anglia and rivers began to flow across the surface of the Pliocene beds. The rivers soon cut down through the unconsolidated deposits and then became superimposed on the folded Cretaceous strata. This explains why we find that many of the rivers of the southern Weald area flow across the highest part of many of the mid-Tertiary anticlines. This is not usual and can only be explained by supposing that the folds were planed off before the initiation of the present drainage. So quickly were the valleys widened that the sheet of Pliocene beds is now reduced to scattered patches on the ridge tops.

In East Anglia, the Pliocene sea laid down very shelly sands, the *Crags*, clearly deposited in very shallow water. The retreat of the sea continued and the highest beds of the Crags form part of a great delta built out by the combined Rhine-Thames into the southern North Sea. One interesting point concerning the fauna of the Crags is that in the basal beds are to be found many forms living today off

our coasts or even further south, but in the higher beds they disappear and are replaced by an increasing number of shells which are to be found today in the colder waters off the coast of Norway.

The Pleistocene Ice Age

This change in the fauna of the Crags must be due to the growth of ice-sheets on the Scandinavian mountains and the gradual cooling of the waters of the North Sea. These mountain glaciers joined together to form great ice-sheets, which at their maximum extent covered all Europe, north of a line extending from the Carpathians across southern Germany to the mouth of the Rhine and then just north of the Thames and the Cotswolds to the extreme south of Wales. To the south of this, mountain blocks like the Alps, nourished their own glaciers, which spread out far across the surrounding low ground. The history of the Pleistocene Period is not a simple one of the growth of these glaciers and then their retreat. In many areas several distinct boulder clays can be found, each one containing different erratics. For example, in East Anglia the lowest boulder clay contains erratics which have been brought right across the North Sea from southern Scandinavia. Overlying it is another boulder clay, full of Chalk and Jurassic fossils, proving that the ice was then coming from the north-west. A still younger boulder clay contains numerous rocks derived from the Cheviots. These must have been brought by glaciers travelling more or less parallel to the present coast line.

Very locally these different boulder clays are separated by deposits which yield the remains of plants and animals, including human implements, of types living in a climate at least as warm as that of Britain today. It is therefore clear that the Pleistocene glaciation was not a single one. There must have been a number of *glacial periods* separated by much warmer *interglacial periods* when the ice-sheets shrank back to small glaciers, like those on the Scandinavian mountains of today. When the ice readvanced, it may have moved along a slightly different track and this would explain the variation in the composition of the different boulder clays. There must have been great oscillations of sea-level, with immense amounts of water locked up in the ice-sheets during the glacial periods, but the melting of the ice-sheets meant that this water was returned to the oceans (p. 88).

As a result of these changes, the surface of Britain was profoundly modified during the Pleistocene Period. In late Tertiary times the upland areas, after their long period of erosion, must have

had gently rounded surfaces, but during the glacial periods, great corries, arêtes and glaciated valleys were gouged out to form the mountain scenery of today. Vast quantities of rock debris were carried away to be deposited in the lowlands, mainly as great featureless spreads of boulder clay, but during the final retreat of the ice many excellent examples of morainic ridges, drumlins, eskers, etc., were formed. At the same time the preglacial drainage of the British Isles was profoundly modified by glacial diversion (p. 72).

The changes in topography were not restricted to glaciated areas, for the oscillations of sea-level affected the whole of the British Isles. During the periods of lowest sea-level, the rivers entrenched themselves in deep gorges. When sea-level rose again, the lowest part of the gorges were submerged to form the beautiful drowned estuaries of our western and south-western coasts.

At last the ice-sheets finally retreated back into the mountains, the sea for the last time submerged the Straits of Dover, Great Britain became an island, the Holocene Period began and geological time ended.

SECTION F

Economic Geology

CHAPTER XIX

Some of the Economic Applications of Geology

THE ordinary principles of Geology can be applied to many problems of economic importance, only a selection of which can be treated here.

Water Supply

Anyone who does any gardening soon learns what may happen to rain after it has fallen. If it falls on a path through which it cannot penetrate, the water will either run off the path or remain standing until it is evaporated by the sun and the wind. Rain falling on the beds usually soaks in, but if the fall is too heavy it cannot soak in fast enough, so pools form which gradually disappear when the rain stops, partly owing to evaporation and partly as they are able to soak slowly into the ground. In a normal summer, the soil soon becomes very dry owing to the seasonal increase in the rate of evaporation aided by the loss of the water that is drawn from the soil by the roots of plants and transpired from their leaves.

The rain that falls on a wider area behaves in the same way. A part 'runs off' impermeable or sodden ground more or less directly into the rivers, a part is returned to the atmosphere by evaporation and transpiration, whilst the remainder percolates or soaks downwards. Water will percolate through the open fissures (joints) of the rocks or through the pores between the particles of the rocks, until it is stopped by a bed, which is neither pervious or porous. Argillaceous rocks are the commonest impervious beds. For some distance above such a watertight seal, all the spaces in the overlying strata will be filled with water. The upper level of the saturated zone is termed the *water-table* and is the same as the rest level (level to which

water will rise after a period of pumping) of wells sunk into the water-bearing stratum or aquifer.

Contour lines can be drawn on the surface of the water-table if the rest level in sufficiently closely spaced wells is known. If this is done at regular intervals, the height of the water-table will be seen to fluctuate considerably, depending partly on the variation in rainfall, but more particularly on the proportion of rainfall that is able to percolate. In the summer this will be small, for evaporation and transpiration are at their maximum. The fluctuation in the height of the water-table is therefore seasonal being, under normal weather conditions, at its lowest in August and September and then rising steadily during the autumn and winter, until in March the effects of increasing evaporation cause a check and then a fall. The amount of this seasonal fluctuation is often of the order of 20 feet or more.

If a water-level contour map is compared with a topographical map of the same area, it will be seen that the water-table follows in a broad way the shape of the ground. Where the water-table cuts the ground surface, springs will occur, particularly at points where there is a ready flow of water through the rocks. Springs usually show the same seasonal fluctuation, failing in the dry weather as the water-table drops. Springs are particularly likely to occur where a permeable bed overlies in normal succession or is faulted against an impermeable stratum (Fig. XIX, 1). The springs may be sufficiently closely spaced to produce a spring line, which is of great help in tracing boundaries between beds. Springs which occur in the bottoms of valleys are often 'bourne springs', especially in Chalk country. The head of a river fed by bourne springs fluctuates considerably in position; in wet years the springs breaking out several miles further up the valley than in dry years.

Water moves through the rocks under the force of gravity and therefore collects in the downfolds. The term *artesian* is given to those basins in which the hydrostatic pressure in the aquifer is great enough to cause water to flow freely from any well sunk in the centre of the basin (Fig. XIX, 1). Such artesian wells are less common than they used to be, for with the growth of population and also the steadily increasing consumption of water per head, water is often being withdrawn by pumping from an aquifer more rapidly than it is received from percolation. Overpumping must cause the water-table to fall, and wells cease to be artesian, have to be pumped and eventually dry up completely.

London is an excellent, but most disturbing, example of a former

artesian basin which is being most severely over-pumped. The fountains in Trafalgar Square, erected in 1844, at first played from

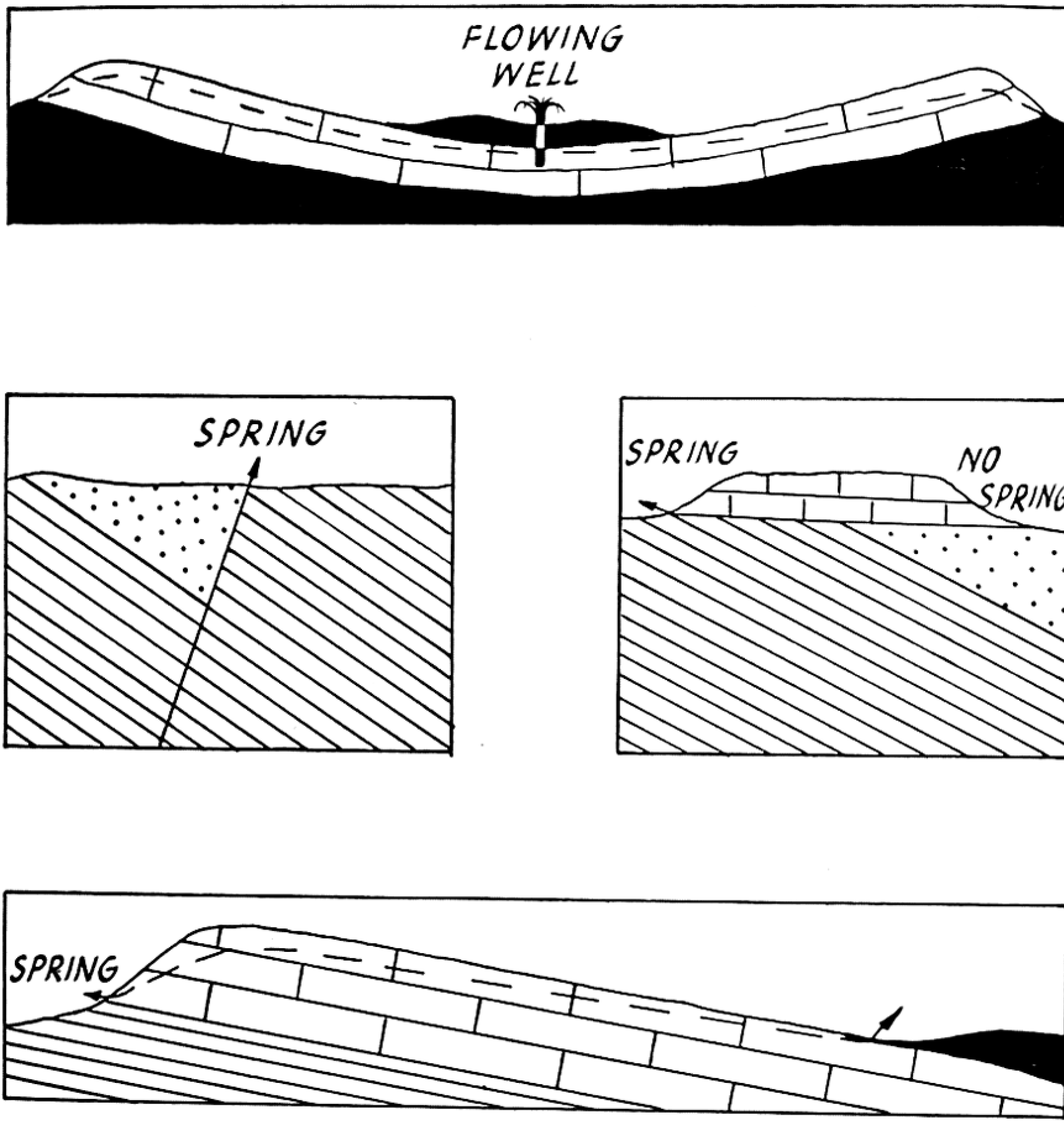


Fig. XIX, 1.—Water Supply

Above:	An Artesian Basin.
Middle, left:	A Fault line spring.
Middle, right:	Springs beneath an unconformity.
Below:	Scarp foot and dip slope springs.

Impermeable beds are in black or lined. The water table is shown in the upper and lower diagrams by a broken line.

the force of an artesian well. But in a few years they ceased to play unless the water was driven by pumps. The rate of fall of the water-table beneath parts of London is in places as much as five feet per year. Wells are running dry, whilst in the Woolwich area springs of

fresh water which used to bubble up on the floor of the Thames have not only ceased, but if pumping in the neighbourhood is too heavy, foul water from the Thames is drawn down through the same fissures into the Chalk.

A geologist dealing with water supply problems has to consider both the quantity and also the quality of the water likely to be obtained at the place where he recommends sinking a well. Quantity is dependant not only on the aquifer being a thick bed with a sufficiently large catchment area at outcrop but also on the freedom with which water can move through the rock to replenish that removed by pumping. The Chalk, the most important aquifer in the British Isles, holds its water in open joints, for the rock itself is extremely fine-grained and of very low perviousness. To obtain a large yield from the Chalk it is usually necessary to drive horizontal shafts for a considerable distance from the bottom of the well so as to cut a large water-holding fissure. In those areas, where fissures are few, the Chalk is notoriously 'tight' and slow yielding.

The quality of the water depends on the amount and nature of the mineral matter which it holds in solution. Chalk water is 'hard', containing considerable quantities of the bicarbonates of calcium and magnesium, producing temporary hardness and of the sulphides and chlorides of the same elements, which are the cause of permanent hardness. When hard water is boiled, a scale of carbonate is deposited increasing the amount of fuel required considerably. Much more soap is needed to produce a good lather in hard than in soft water. In the home, hard water may be only a minor inconvience, but for industrial purposes the increase in costs may be very serious.

The water may also be too brackish or it may be corrosive, containing so much chloride that boiling produces sufficient hydrochloric acid for metals to be attacked or it may be too ferruginous, a common cause of iron mould. Poor quality water can be purified, but the cost may be appreciable. It is more important that the water is bacteriologically pure. This is normally the case with underground water but serious and sometimes fatal outbreaks of diarrhoea, dysentery, not to mention cholera, typhoid, etc., have occurred, even in the British Isles, when decaying organic matter has been washed through fissures into aquifers. In all water undertakings constant watch is kept against the possibility of organic contamination and, if necessary, the water is treated with chlorine or by other methods.

ENGINEERING APPLICATIONS

The construction of dams, reservoirs, tunnels and other major engineering works must alter the stresses to which rocks are subjected. If the alteration is too great, movement of rock and soil may occur, perhaps overwhelming the works or at least causing delay and additional cost. The geologist is able to give advice as to the nature, water-holding properties, stability and structure of the site, so that suitable constructional methods can be adopted and precautions taken at places where trouble is expected.

Considerable attention has to be paid to geological factors in building a reservoir. Rainfall and especially runoff from the gathering ground must be sufficient to provide enough water for storage. The reservoir must be watertight and the dam capable of resisting the thrust of the impounded water. Suitable conditions are usually found in hilly or mountainous areas of predominantly argillaceous rocks, for runoff will then be high and the floor of the reservoir should not need concreting or puddling. But if there are seams of porous rock, and if these dip away from the reservoir, then leakage may occur. The ideal site should therefore be synclinal in structure. The foundations of the dam should rest on solid rock, preferably not on limestone, for if the stored water is at all acid, solution of the limestone may take place. This will cause leakage and if this become excessive, the dam may collapse and dangerous floods rush downstream.

Most of the known cases of dam failure are due to inadequate appreciation of the geology of the site. In one case a dam was built across a fault, throwing schist against a conglomerate containing seams of sand and thin beds of gypsum. A worse site can scarcely be imagined and the inevitable happened. As soon as the reservoir was filled, water began to leak through the porous sand whilst the gypsum began to dissolve away. In a few months the foundations were so weakened that the whole dam collapsed.

The nature of the load carried by the streams into the reservoir must also be carefully considered, for there is the risk of such rapid deposition of the traction and the suspension load in the still waters of the artificial lake, that the storage capacity of the reservoir may be rapidly reduced by silting. It may be necessary to allow the water to flow through silt traps which can be emptied periodically.

Glacial deposits are often a most serious problem. Their bearing capacity is often low, their characters often vary in a short distance and they may contain waterlogged seams of sand and gravel, whilst

boulder clay is often difficult to excavate. It is also difficult to estimate their thickness without putting down trial borings, and if these are not sufficiently closely spaced, deep narrow preglacial valleys may be undetected, and the cost of excavation to carry the foundations down to solid rock may be much greater than was estimated.

Waterlogged ground of any kind is always liable to cause trouble, for it is weak and very apt to slide into excavations. Wells may have to be sunk and pumped heavily, so that the works can be carried out in the overlapping cones of depletion of the wells or the area may have to be frozen or the porous beds artificially cemented by injected chemicals.

Sliding is also likely to occur when planes of weakness in the rocks, whether bedding planes, joint planes, cleavage planes, fault planes, etc., are inclined towards excavations. It is therefore most important to have a precise knowledge of the geological structure of the site. Surface mapping may not give sufficient information, for there may be a cover of boulder clay or the works may pass through a plane of unconformity. Trial pitting or trial boring may be necessary and will be done in the most efficient manner under geological advice.

Building Stones

Fortunately natural stone is still used to some extent for building in preference to bricks and artificial stones, such as concrete, composed of rock fragments mixed with a cementing material. Stone used for building must be durable, capable of being worked into the required shape, pleasing in appearance and, of course, its cost may be the deciding factor. The cost of the stone is determined partly by transport charges and partly by the expense of quarrying and dressing it. Quarrying costs depend largely on the amount of overburden and side burden which have to be shifted to obtain the stone. The size of the blocks obtainable is determined by the spacing of planes of easy splitting such as bedding and joint planes. The splitting may be done by explosives but often, as in the Portland Stone quarries, hammer and chisel are preferred, for there is less risk of the stone breaking in the wrong place and producing smaller blocks.

The cost of dressing the stone to the required shape is determined partly by its hardness and also whether the stone can be worked easily in any direction or whether, like many sandstones, it tends to break in a rectangular pattern along the bedding and joint direc-

tions. Portland Stone, perhaps the most widely used of building stones, is a '*freestone*' and can be carved in any direction, like wood without a well-marked grain.

Appearance is usually more important for interior than for exterior work. The decorative stones mainly used for interiors are usually polished and include a wide variety of rocks. The limestones used are mostly those containing fossils, set in a groundmass of a different hue, so that the stone is not too monotonous. Examples include Purbeck Marble, a limestone with numerous gastropods from the highest Jurassic strata, Hopton Wood Stone, a bed of crinoidal limestone from the Carboniferous Limestone of Derbyshire and the coral limestones or 'Devon Marble' of the marine Devonian strata of Torquay. To the geologist the term 'marble' given to these rocks is inaccurate, for their well preserved fossils prove that they have not been metamorphosed. Marble is here used as a trade term, implying a rock that can be cut and polished. Similarly in both the building and the roadstone trades the term 'granite' has been applied to many hard rocks, some of which are not even of igneous origin as for example Ingleton Granite from the Pre-Cambrian of Yorkshire, a tough greywacke and the 'Petit Granite' of Belgium, which is really a compact limestone. Igneous and metamorphic rocks used for decorative purposes are referred to on pp. 172 and 175.

The durability of a building stone is determined mainly by its resistance to chemical weathering, which is much more severe in industrialized areas than in the country where the stone may have been quarried. It has been estimated that nearly five million tons of sulphur dioxide are poured into the atmosphere of Great Britain every year from chimneys. The sulphur dioxide forms in rain water a very dilute solution of sulphuric acid, which may however be strong enough to attack, etch and weaken stone at a surprising rate. Portland Stone is able to resist this attack much better than many other oolitic limestones, such as Ham Hill Stone from Somerset or even Bath Stone. Any lines of weakness are soon picked out and if the stone contains 'vents' or calcite-filled cracks as in the Anston Stone from the Magnesian Limestone used in the Houses of Parliament, these cracks are soon opened with the result that large blocks may fall off the building, especially if decoration is elaborate and the stone undercut.

The way in which the blocks are placed in the building is important. The stone should always be 'in the bed' as it lay in the quarry, for if it is edge bedded (Fig. XIX, 2) any easily etched layers

will produce unsightly grooves, whilst face bedded stone is very liable to flake. The mingling of two different stones in the same building, for example limestone and sandstone or limestone and dolomitic limestone, accelerates decay, the one stone producing solutions which are able to attack the other. The best method of preventing the too rapid disfigurement of stone, particularly of limestone, is regular washing with pure water, so that any deleterious crusts are removed.

A walk through almost any town or city can be made interesting, by identifying the various building stones and by looking for any evidence of their relative durability.

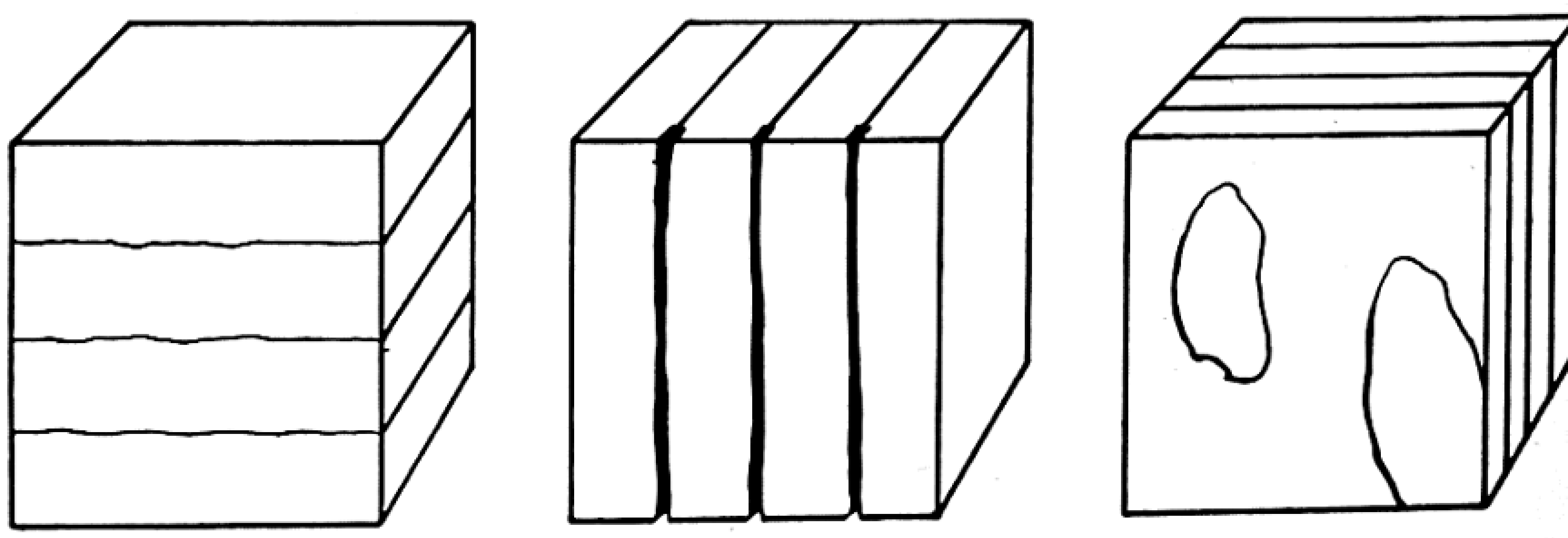


Fig. XIX, 2.—The Weathering of Blocks Set Different Ways in a Building

Welsh slate and later brick tiles, have almost completely ousted the more fissile limestones and sandstones as roofing material. Not the least attractive feature of the old stone houses of the Cotswolds or of the Weald are their roofs of heavy slabs of Stonesfield Slate or ripple-marked Horsham Stone. Again trade and geological names are at variance, for Stonesfield Slate is not a metamorphic rock, but is a particularly thin-bedded oolitic limestone found in a small area in Oxfordshire. The blocks were wrought in the summer and left out during the winter and if this was severe enough, the 'frost wedge' would split the stone along the bedding into slabs. Welsh roofing slate is a true metamorphic rock, for it splits not along the bedding, but along the closely spaced cleavage planes. One of the main causes of the decay of the Welsh slate industry is the great amount of waste that has to be shifted to obtain suitably cleaved blocks, the proportion of waste and poor-quality material being sometimes as much as 90 per cent of the stone quarried.

Road Stones

In quarrying stone for use on the roads it is not nearly so important to extract it in large pieces. Indeed it is an advantage to work stone that breaks easily into pieces a few inches across. Again, appearance is not important. The essential feature is that the rock should be tough and fairly even-textured. Coarse-grained igneous rocks, such as granite, are usually unsuitable, for they break under the stresses produced by traffic along the cleavage planes of the feldspars or at the surfaces between the different minerals. Fine-textured rocks such as basalt and dolerite are quarried very extensively in many parts of the British Isles and with their tightly interlocking crystals usually form durable road stones. Most sedimentary rocks are too soft, though sedimentary quartzites are used where they occur in thick-enough beds. For example a ridge of steeply dipping Cambrian quartzites near Nuneaton is seamed with great road-stone quarries. Carboniferous Limestone, is used on a considerable scale as a top dressing for roads on which the rock chips are bound together by bitumen. Limestone, though relatively soft, has a strong affinity for bitumen and therefore the limestone chips are less easily torn out of the road than are chips of many harder, but less adhesive, rocks. Metamorphic rocks are usually not very suitable, for they are traversed by numerous fracture planes along which the stone may fail.

Concrete is being increasingly used as a carpet for roads. It can be made either of fragments of any tough rock crushed to the required size or from gravels or pebble beds.

The Search for Oil

As stated on p. 200 mineral oil is very apt to migrate from its place of formation. Oil is volatile and, unlike water, will move up the dip of the rocks until it either reaches the surface and evaporates or it is trapped beneath an impermeable layer.

The task of the geologist searching for accumulations of oil is first to decide whether oil is likely to have been formed in the area and secondly to find structures in which the oil may have accumulated. He must consider the paleogeography of the area and its geological structure; both of which depend on as complete a knowledge as possible of the succession and lithology, i.e. the stratigraphy, of the region.

'Reservoir rocks' in which oil may accumulate must be, like good aquifers, either strongly fissured or of high porosity, conditions most commonly met with either in massive limestones or sands and

sandstones, whilst the migration of oil will be stopped by a fine-textured stratum such as clay or shale.

Oil is particularly likely to accumulate in domes beneath an impermeable layer. In Fig. XIX, 3, are shown some of the other structures in which oil may be trapped. In any structure it is usual to find a gas zone immediately below the cover rock overlying the oil-bearing zone beneath which the reservoir rock is usually saturated with water, often brackish.

The oil is obtained by boring through the overlying rocks but if the boring is located too near the crest of the structure it may only yield gas, which may however be of value, either for the by-products it yields or directly for illumination and other purposes. But usually such a 'gas well' is sealed off, for the expense of pumping oil to the surface will be avoided if the gas pressure in the reservoir rock is great enough to force the oil to the surface. A well located too far down the flank of the structure will yield only water. It is therefore a question, not only of locating a suitable structure, but also of sinking the wells in a fairly narrow belt on the structure.

Oil wells are usually much deeper than wells for water supply, depths of several thousand feet being quite common. A mile or so beneath the surface the structures may be very different from those shown at outcrop. A major unconformity may have been passed through or as in Persia the presence of thick beds of salt and gypsum, which flow under stress, may mean that the structures in the rocks above the salt series are very different from those beneath it. The oil geologist may therefore be unable to elucidate the structure of the area by surface mapping alone.

His mapping of the area would commence probably with the examination under a stereoscope of overlapping pairs of aerial photographs. *Photo-geology* is of great value in relatively unknown country, like most of the areas which the oil geologist has to investigate. The area may not have been properly surveyed topographically, so that the aerial photographs will provide in the first place an invaluable base map. A trained observer can deduce from stereoscopic examination a surprising amount concerning the structure and even the nature of the rocks present. Their nature is indicated by the form of the ground, and often by the type of vegetation, the direction and amount of dip is shown by the scarps, faults may be indicated by fault-line scarps or by sudden changes in the drainage pattern and so on. The interpretation of the photographs must be checked by examination of the beds on the ground, fossils must be collected to place the stratigraphy of the area on a proper basis but photo-

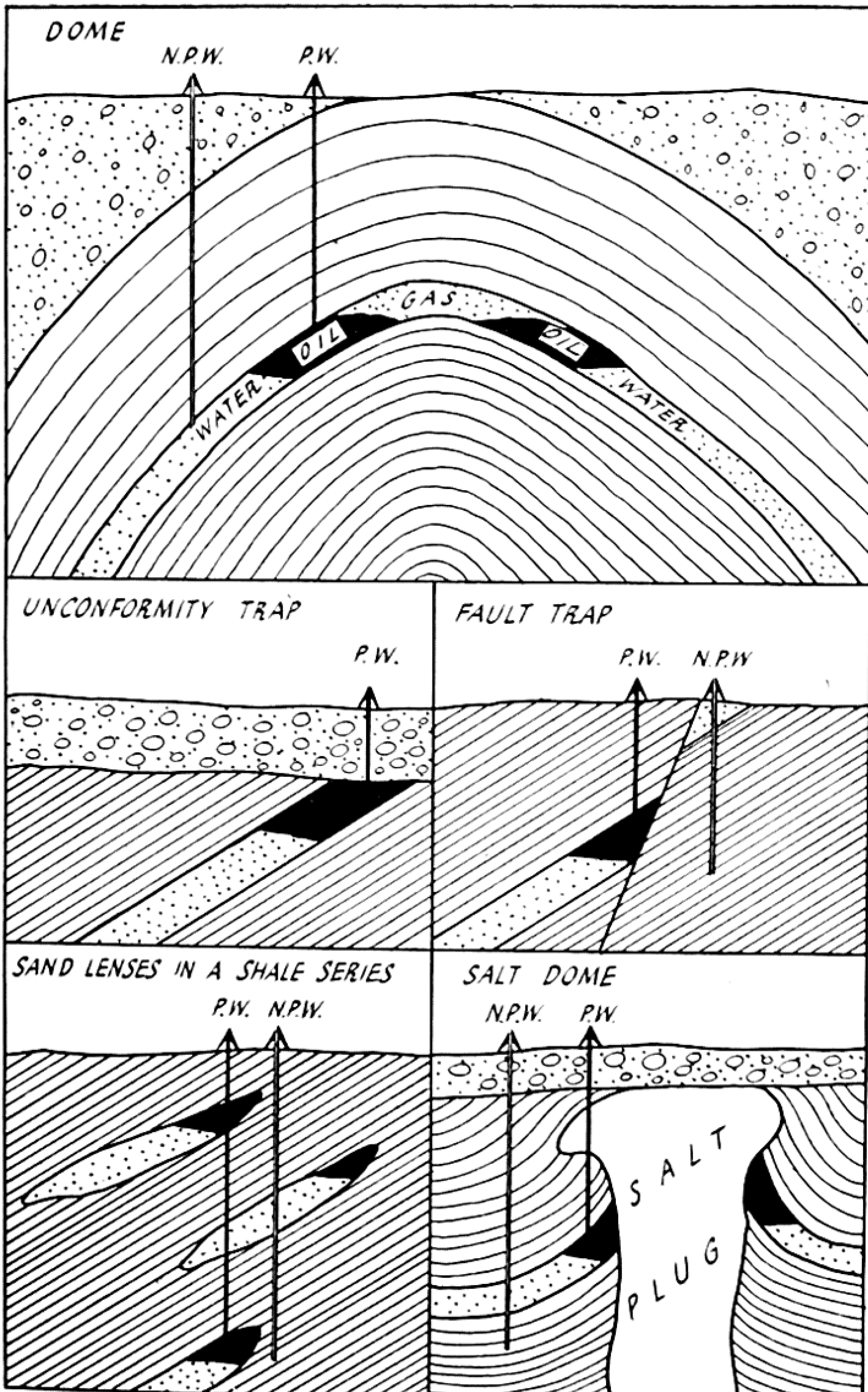


Fig. XIX, 3.—Some of the Structures in which Oil may Accumulate

Oil accumulations in black.
P.W.: Productive Well.
N.P.W.: Non-Productive Well.

geology enables this field work to be concentrated on the areas of greatest importance or with the best exposures, whilst in regions of very thick vegetation details may be shown by the photographs which would be very difficult to detect by unaided ground survey.

If the geologist is attempting to detect structures at great depth, structures which are not deducible from the surface geology, then he will turn to the geophysicist for help. By use of the methods described on pp. 295–7 promising areas are indicated, but whether or not they contain oil can only be proved by drilling and then the geologist must make a detailed log of all the beds penetrated.

Drilling is normally by the rotation method, with the bit, usually armed with diamonds, rotating at the end of an ever-increasing length of steel tubing. Water laden with mud is passed down the centre of the pipe, which is of smaller diameter than the bit. This liquid, carrying with it the chips of rock ground off by the bit, rises to the surface between the sides of the hole and the pipes. The chips are collected and it is from them that the geologist must deduce the nature of the beds penetrated, their thickness and obtain any evidence that he can from fossils, especially very minute forms like foraminifera, as to the age of the rocks. If necessary, cores or cylinders of solid rock can be obtained, but coring is slow and adds greatly to the cost, for each core has to be lifted perhaps a mile or more to the surface, before the special core barrel can be lowered again and drilling recommenced. Coring is therefore only used when it is essential to obtain more evidence than can be gained from the chips.

The record of the well is compared with those of any neighbouring wells and by plotting the variation in thickness of particular beds, by drawing contour lines on easily recognized strata, the geologist is able to build up gradually a three-dimensional picture of the structures underground and to estimate with increasing accuracy the oil reserves of the field and the best place to sink new wells to replace those which are running dry, which happens fairly quickly if the reservoir rock does not yield its oil very readily.

Sub-Surface Investigations

The ordinary methods of geological survey can only be used if the rocks are reasonably well exposed. Additional exposures can be made by digging or, if the rocks are soft enough, by boring into them with augers. Both digging and augering take time, whilst the depth reached is obviously limited. The amount of augering and trial hole digging done is usually determined by economic factors. The staff of an official geological survey normally mapping in this country on the

scale of six inches to the mile, but abroad often on smaller scales, have to work to a programme and therefore have only a certain time in which to complete the survey of each map sheet. Under such conditions only a limited amount of augering can be done, and that usually to a depth of but a few feet. On the other hand, if the site of an engineering project is being investigated, then it is obviously desirable to carry out a sufficient amount of trial pitting and deep augering to obtain full information as to the nature and thickness variation of the rocks on which the foundations are to be built. For example, the investigation of the site of the Battersea Power Station in London involved the sinking of 73 trial borings and 8 trial pits. The foundation had to be carried down through the alluvial deposits of the Thames to the underlying London Clay. The site was on the edge of the Buried Channel of the Thames and it was known, from wells previously sunk for water in the neighbourhood, that these alluvial deposits varied very rapidly in character and thickness. Sufficient trial borings were made, under geological supervision, to enable a contoured map, with the contour lines at 10 feet vertical interval, to be drawn of the upper surface of the London Clay. The cost was £3500, but this was only about one five-hundredth part of the cost of erecting the power station and it was saved many times over by the buildings being designed without an excessive margin of safety, which might have been the case if the bearing load, shear strength, etc., of the materials on which the foundations were built had not been so thoroughly known from the samples obtained during the site investigation.

In Nigeria it has been found possible to trace the line of mineral veins hidden beneath a thick cover of residual deposits by the spectrographic examination of the twigs of trees. The roots of the trees penetrating downwards to the buried mineral veins absorb very minute quantities of lead, zinc and silver, which are carried upwards to the twigs. The twigs of trees growing away from the veins do not contain these 'trace elements' and hence the position of the veins can be detected. In a sense this is merely a refinement of augering and is obviously a method that can only be used where the veins are near to the surface.

Geophysical Methods are used for still deeper investigations, particularly in the exploration for oil, where the reservoir rocks may be at a depth of thousands of feet and further may lie beneath a major unconformity, so that the structures visible at the surface are unrelated to those at depth. Geophysical prospecting consists essentially of very accurate measurements of the variation over a

limited area of such physical properties as gravity, magnetism, the passage of shock waves and of electric currents. The instruments used, though of great sensitivity, have to be robust, so that they can be carried safely in trucks, or even in the case of gravimeters and magnetometers used from low-flying aircraft, whilst gravity surveys of parts of the ocean floors have been made from submarines. Geophysical surveying is therefore not restricted to the land areas and as fresh techniques are developed it will give more and more information as to the nature of the materials beneath the floor of the oceans.

Gravity Survey. The average acceleration of a body falling freely under gravity is 981 cm. (roughly 32 feet) per sec. per sec. or 981 gals. Gravimeters are so sensitive that they measure the force of gravity in fractions of a milligal (the thousandth part of a gal). These measurements must be corrected for latitude (for the Earth is not a perfect sphere, but is flattened very slightly at the Poles, so that the force of gravity is a few gals greater there than at the Equator), for the height above sea-level of the station where the gravimeter is set up and also for any extra pull exerted by the topography around the station. The corrected measurements are then plotted on maps, so that isogals (lines joining all places where the force of gravity is the same) can be drawn. The isogals show the position of 'gravity highs', where the force of gravity is a few milligals greater than elsewhere, due to the presence at depth of rock of greater density than the surrounding country rocks, and of 'gravity lows' underlain by rocks of abnormally low density (Fig. XIV, 7).

Magnetic Survey. In a similar manner, after a magnetometer survey, it is possible to construct a map of the magnetic anomalies, which are left unaccounted for after corrections of the type used in gravity work have been applied to the readings. The anomaly map must therefore show the variations in the magnetic properties of the rocks underlying the area. But only those rocks that contain the mineral magnetite are appreciably magnetic and therefore the magnetic method is of much more limited application than the gravity method and is used mainly for the tracing of hidden dykes and other igneous bodies and of mineral deposits.

Seismic Survey is probably the most widely used geophysical method. In addition to oil field work and the detection of mineral veins, measurements have been made of the depth of glacial fill in valleys in which reservoirs might be built and of the thickness of ice beneath glaciers and ice-caps. Seismic Survey has developed from the investigation of earthquakes (*see* Chapter XIV). In this case the shock waves are produced by an explosion and are recorded by a

number of geophones, arranged either in the form of a fan so as to cover a wide area or in a straight line to give a profile. The time of arrival of the shock waves at each geophone is recorded photographically. It is necessary to fire the shot in unweathered rock, so the shot hole has often to be of considerable depth. The velocity of transmission of the shock waves depends on the nature of the rocks through which they pass, being greater in the more compact types, whilst reflection and refraction of the waves occurs at surfaces of discontinuity separating masses of rock of different physical properties. By analysis of the records made by each geophone, it is possible to determine the depth of such surfaces and with sufficient data to produce a contoured map to show the form of such a surface.

Resistivity Survey. In this method measurements are made of the resistance of the rocks to the passage of an electric current. Resistivity is determined not so much by the nature of the rock as by the amount of water which it contains. The composition of the water is also of importance for fresh water is a much better conductor (i.e. of lower resistivity) than salt water, whilst completely dry rocks are of still greater resistivity. This method is useful for determining the position of hidden fault zones and mineral veins, provided they are water-bearing and traverse drier rocks, or in measuring the thickness of waterlogged drift deposits overlying drier solid rocks. Resistivity surveys, like magnetic surveys, are therefore only successful under rather specialized conditions. Two pairs of electrodes are required. An electric current is passed by car batteries between the outermost pair and the difference in potential is measured between the innermost pair. The spacing of the electrodes governs the depth of penetration of the current and hence by varying this it is possible to determine the depth of surfaces at which there is an abrupt change in resistivity.

The real difficulty in geophysical surveying is not in making the measurements, but in the interpretation of the results obtained. The task of the geologist is to analyse the structural implications of the maps and profiles and to suggest the age of the strata in contact along the surfaces of discontinuity. This is not an easy matter, for specimens of the rocks at depth have not been obtained, whilst there is always the possibility that the measurements may have shifted from one surface to another. For example a rock body of distinctive physical characters may lens out beneath a surface of unconformity. Contour lines may have been drawn in one part of the area on the surface of unconformity and elsewhere on the upper surface of this bed, which

is dipping away from the plane of unconformity. Failure to realize this will naturally give a misleading picture of the underground structure of the area, as the plane of unconformity will be regarded as having been warped where the basset edge of the underlying layer meets it. Again, it is possible to suggest that the anomaly detected at a particular point by a gravity survey may be due to so many thousand feet of rock of certain specific gravity overlying denser rocks but the suggestion is only one of many possibilities; which is correct can only be proved if a boring is sunk and specimens of the underlying rocks obtained.

Geophysical surveys, especially if the seismic or gravity methods are used, do however indicate the most likely places in which to drill so as to penetrate structures, such as domes, which may yield oil. In the early days of the search for oil, most of the wells sunk were 'wild cats', that is, their site was chosen by guesswork. Nowadays most holes are 'controlled', in the sense that their location has been determined by scientific methods, either by extrapolation from nearby wells or by geophysical prospecting. Geophysical surveys have, so far, been most extensively used by the oil companies, but as indicated above, these methods of probing beneath the surface rocks can be of considerable value to the mineral prospector and to the civil engineer as well as to those engaged in research on such topics as the three-dimensional shape of glaciers and ice-caps or the thickness of sedimentary beds on the continental shelf.

APPENDIX I

Interpretation of Geological Maps

A GEOLOGICAL map is a topographical map overprinted with colours, showing the outcrops of the different beds, and with symbols indicating dips, faults, mineral veins, etc. At the sides of the map is printed the legend or succession of the beds, the sedimentary rocks being arranged in order of deposition, with the oldest at the bottom. On the maps of the Geological Survey, each bed is marked by a distinctive notation as well as colour. The initial letter marks the system, e.g. a for Cambrian, h for Cretaceous, etc., and the beds of each system are numbered from below upwards. Metamorphic rocks often bear Greek letters, whilst for igneous rocks the letters indicate as far as possible the nature of the rock, e.g. qD for quartz-Dolerite, whilst the age of an extrusive rock is shown, e.g. Rd′ for Rhyolite of Lower Carboniferous date.

On many maps, part or all of the succession is drawn out to scale, with the more distinctive beds, limestones, coals, etc., correctly spaced. The position of unconformities is usually indicated on the legend, whilst beds that vary considerably in thickness are shown with triangular outlines.

The first step in studying geological maps is to gain familiarity with the conventional signs and symbols used (*see* Fig. XX, 1) and with all the information printed on the map.

In the following pages reference is made to two 1 inch to the mile maps of the Geological Survey, Brampton (Sheet 18) and Brighton (Sheet 317).

SOLID AND DRIFT EDITIONS

For areas such as Brampton, where peat and glacial deposits are extensively developed, two editions of the Geological Survey maps are published. The Drift Edition shows all the Quaternary deposits that are present, the pre-Quaternary beds being only marked where they are not hidden by drift. This edition, therefore, shows those beds that actually form the surface of the ground. On the Solid Edition, only pre-Quaternary strata, out of which the present landscape has been carved, are

shown, the drift deposits, formed during the erosion of the land-surface, being assumed to be absent.

The exact position of boundaries of the solid rocks beneath a thick cover of drift is often uncertain. On the low ground of the western part of the Brampton sheet, where the drift cover is thick, the boundaries of the Carboniferous and New Red Sandstone beds are, with few exceptions, marked by broken lines. On the high ground to the east, the solid rocks outcrop, and there many of the boundaries are firm lines indicating that they have been traced accurately. But on these heights there is much peat and downwash. The yellow 'Firestone Sill' can be seen to have a firm boundary for some distance, then this becomes broken and the outcrop ends; not because the bed has thinned out, for the outcrop has not tapered in width, but simply because the 'Sill' is hidden by the drift.

The Brighton area, on the other hand, was not glaciated. Drift deposits are of small extent, consisting of Alluvium (which is always shown on both Solid and Drift editions) and Gravel on the low ground and Clay-with-Flints on the Downs. Only one edition (Solid with Drift) is necessary, for the drift deposits are not extensive enough to obscure the solid rocks appreciably and the same map can be used to show either the structure of the area or the nature of the ground surface at a particular point.

Section Drawing

1. *The Profile*

Relief is shown by contour lines drawn at 50 feet O.D. (above Ordnance Datum), then at every hundred foot interval up to 1000 feet O.D. and above that at vertical intervals of 250 feet. In addition other determined points, often on hilltops or in valleys, are shown. Spot heights are marked by a dot with the level beside it, e.g. . 267, whilst if the dot is in a triangle, the point is a trigonometrical station.

The profile of the ground is obtained by laying a strip of paper along the line of the section and marking on it each contour crossing and all spot heights. If the geological colouring is heavy, it is often difficult to see the contours and after working along the section, it may well happen that some contours have been missed; this will be indicated by a gap in what should be a consecutive sequence of numbers. Look for the missing contour on either side of the section line and then trace it inwards. It may have been obscured by some other detail, buildings or the heavy line of a road.

When all the contours have been found, lay the strip of paper on a piece of squared paper and mark dots at the correct height above the datum line for each determined point. Join the dots with a smooth line to complete the profile.

2. *Vertical Exaggeration of the Section*

It is often necessary to draw a section with the vertical scale greater

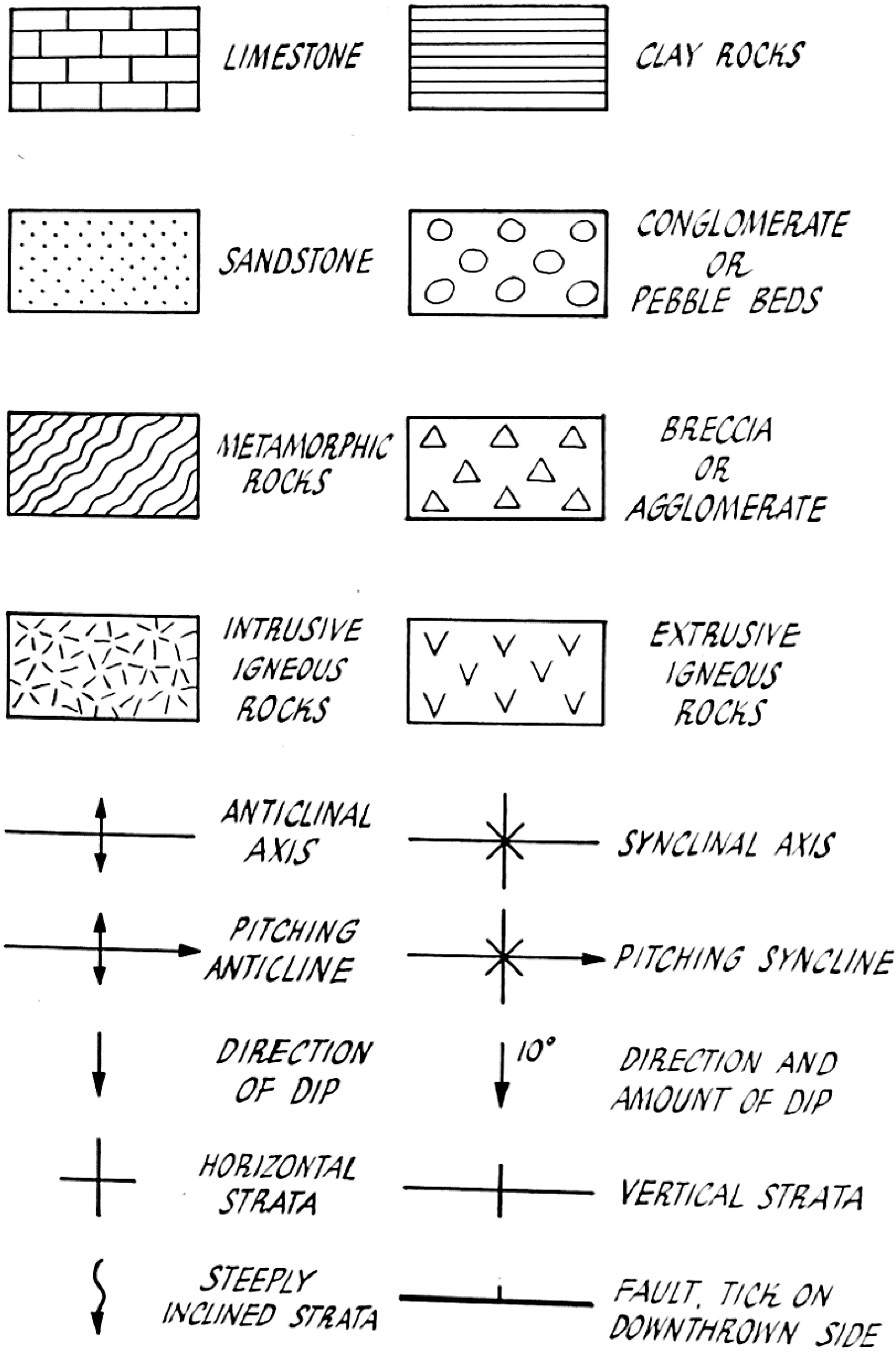


Fig. XX, 1.—The Commoner Conventional Symbols Used on Geological Sections and Maps

than the horizontal scale. True or natural scale sections, with the same vertical and horizontal scales, show the dip of the beds accurately, but if drawn for 1-inch maps, points 528 feet apart in altitude will only be separated by 1/10th of an inch on the profile. Except in very rugged country, a profile on this scale will be nearly a straight line and also unless the section is carried far below sea-level, there will not be sufficient room to show the lie of the beds easily. On the other hand, if the vertical scale is many times the horizontal, all slopes, whether of the ground or of the beds, will be greatly exaggerated. This will give a very misleading picture of the structure.

A vertical scale of 1 inch to 1000 feet is usually satisfactory for a map on the scale of 1 inch to the mile, for a vertical exaggeration of 1 : 5.28 is not too distorting, whilst paper squared in inches and tenths can be used.

3. *The Lie of the Strata*

Transfer the outcrop of the different beds to the profile in the same way as for contours. To complete the section the beds must be drawn dipping correctly from the places of outcrop. On many maps arrows with a number beside them mark places where the dip has been measured at the point of the arrow. Dip arrows, however, are often widely scattered over the map and, in any case, they are only points on what may be a curving surface, so do not assume that the beds will continue dipping indefinitely from the arrows. The slope of the beds along the section line is inserted by considering, with any help given by the dip arrows, the relation between the shape of the outcrop and the form of the ground. The chief rules are:

(i) horizontal beds follow the contours,

(ii) the straighter the outcrop, the steeper the dip.

For example on the Brampton sheet, the dark blue outcrops of the limestones around 56,51[1] are relatively straight and the dips vary between 45° and 70°. Around 59,52 the Firestone Sill has a curving outcrop. At 586,519 the 1500-feet contour is in the middle of the outcrop, but where the 60 grid line crosses the Sill, its outcrop is well below and approximately parallel to the same contour, proving that this bed is dipping eastwards at a low angle. The eastward dip of the beds must therefore flatten considerably between 56,51 and the 60 grid line.

Repetition of the outcrops is usually due to *folding*. The Sandgate Beds (h^2 ‴) are crossed three times by the 21 grid line on the Brighton sheet. Around Henfield (21,16) their outcrop swings round that of the younger Folkestone Beds. With the younger beds in the centre, the structure must be synclinal. As the outcrops of h^2 ″ and h^2 ‴ are narrower to the

[1] The National Grid, printed along the margins of post-war maps, enables points to be fixed with precision by either a four- or a six-figure reference. *Eastings are always given before northings.* On the older maps latitude and longitude can be used, though not so easily as the Grid. Avoid such statements for locating points as 'near the Waterworks by the western margin of the map'.

south than to the north of Henfield, this syncline must be asymmetrical with a steeper dip on the southern limb. To the south of this syncline there must be a complimentary anticline, for the Sandgate Beds reappear again on the south side of an area of Weald Clay (h^1). To the south of 21,13 the beds dip steadily southwards at a low angle. This is shown by the regular order and form of the outcrops, those of the Melbourn and Chalk Rocks cutting the contours very obliquely. The presence of numerous outliers and some inliers is additional evidence of a gentle dip (Fig. XX, 2).

Outliers, as at 203,104 and 243,105 on the Brighton sheet, are patches of younger rocks entirely surrounded by older beds. They are outlying fragments of a stratum, which has been partly removed by erosion. *Inliers*, on the other hand, are older beds entirely surrounded by younger strata and occur in the bottoms of valleys, where erosion has cut through an overlying stratum. A good example is at 135,115 where the Middle Chalk outcrops in a dry valley. At the head of the valley the slope of the ground, shown by the close spacing of the contours, is steeper than the dip of the rocks, so the valley floor has cut down through the Upper Chalk, but where the valley floor flattens, it is inclined less steeply than the beds and the Upper Chalk descends to the valley bottom and sweeps round the outcrop of the Middle Chalk. The outcrop of the Lower and Middle Chalk around 38,08 is an anticlinal inlier along the axis of a gentle dome, whilst at 05,49 on the Brampton sheet the inlier of d beds is due to a small horst.

On the Brampton sheet is an example of an anticline, which can only be detected by careful scrutiny of the dip arrows. At 557,510 bed d^1 is dipping eastwards beneath the d^{2a} beds in normal succession. At 553,507 is another outcrop of d^{2b}, but as it is faulted against d^1, the outcrops could be explained by a strike fault throwing against the eastward dip. At 552,510, however, d^1 is shown to be dipping westward, so an anticline must be inserted on the section (Fig. XX, 3). This example demonstrates how important it is to use every scrap of evidence shown on the map, and also to look on either side of the line of section.

Normal *faults*, whether dip or strike, always hade towards the younger rocks. With the help of the legend, the direction of hade can be easily determined, e.g. on the Brighton sheet, the fault at 23,13 must hade and downthrow to the south, but the two faults near 28,21 must hade towards each other, forming a small rift, in which a tongue of h^1 has been let down between the outcrops of h'''. If the table of strata is sufficiently detailed, it is often possible to work out the exact throw of faults. The fault at 650,520 on the Brampton sheet throws the base of the Great Limestone on the east against the Little Limestone on the west. On the legend these two horizons are 180 feet apart and therefore this fault must downthrow 180 feet to the west. On the Brampton sheet the direction of downthrow of faults is marked by a prominent bar at right angles to the fault line, but on some sheets these bars are not shown. Even then, there should be little difficulty in determining the direction of downthrow of faults, provided

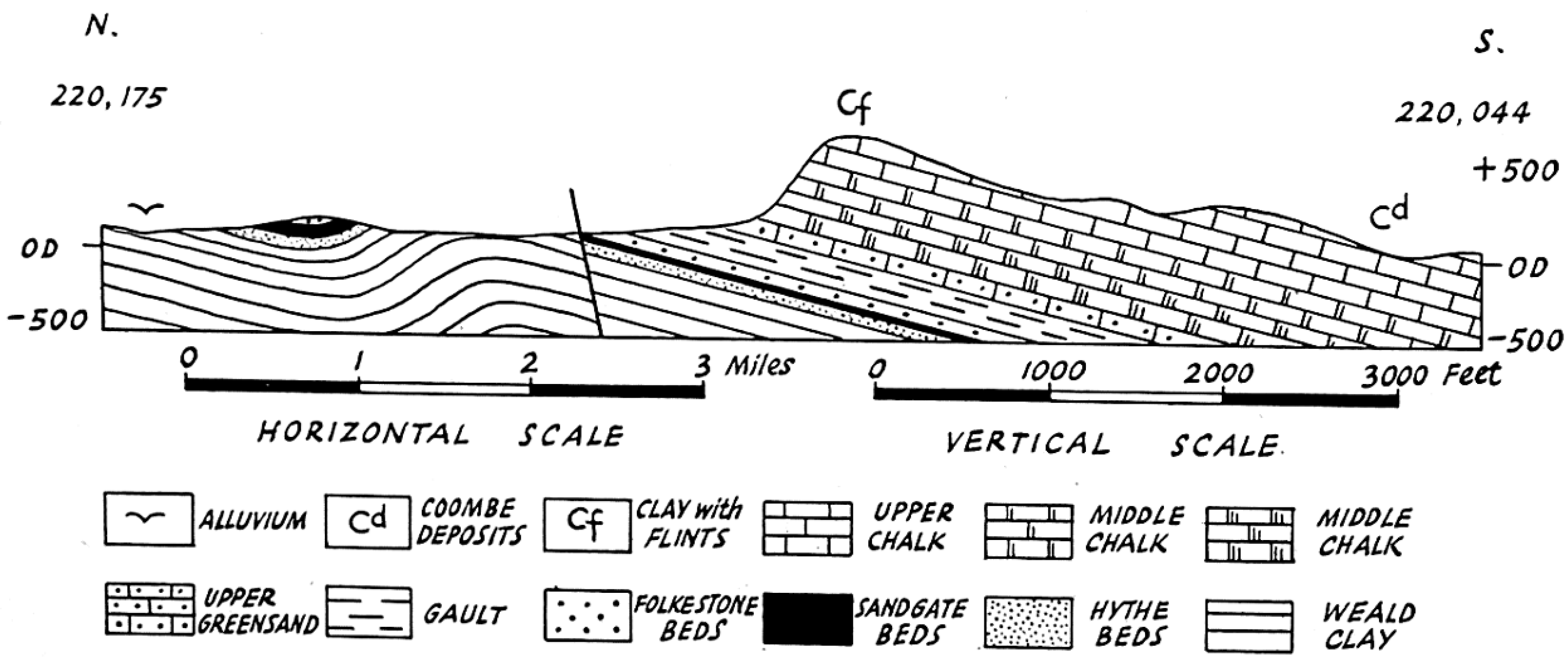


Fig. XX, 2.—Carefully Drawn Profile Section Across the Brighton Sheet

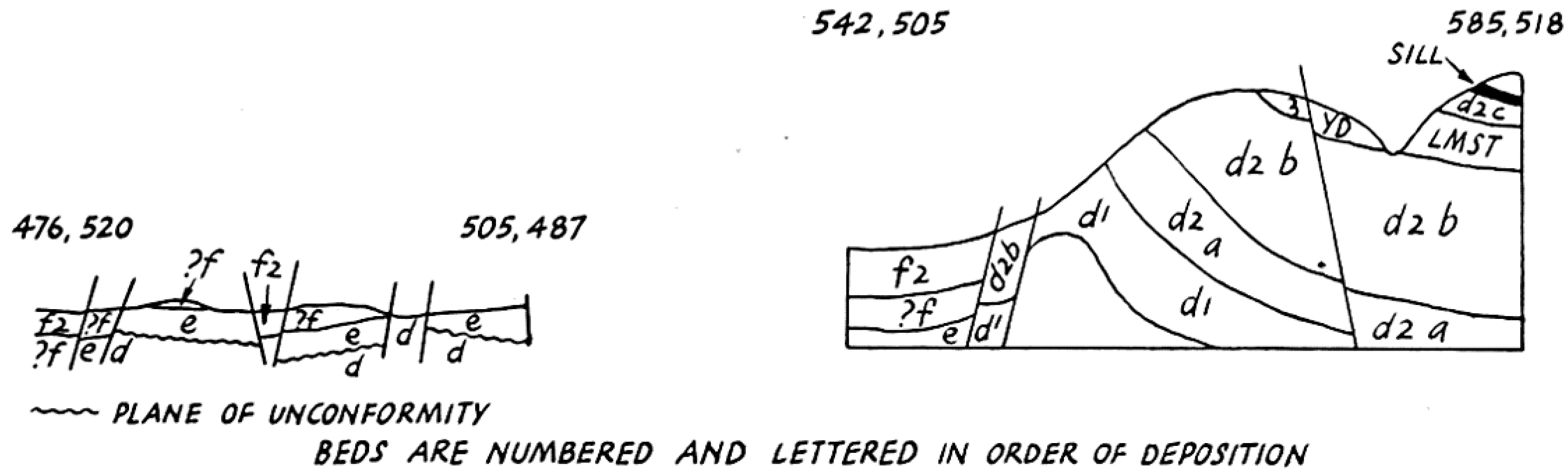


Fig. XX, 3.—Sketch Sections Across the Brampton Sheet

The beds are numbered and lettered in order of deposition. Those shown are the minimum needed to indicate the structure clearly.

that the relative age of the rocks on either side of the fault can be learnt from the legend.

On the Brampton sheet there are two different forms of *igneous intrusions.* The narrow, almost straight, outcrops extending from 623,616 to 695,628 and from 400,503 to 430,488 must be nearly vertical dykes, but the other red outcrops, nearly parallel to the bedding of the Carboniferous strata, must be sills, which do not however maintain a constant horizon. At 583,523 for example the sill crosses gradually from below to above the Little Limestone Coal.

Sketch Maps and Sketch Sections

Accurately drawn and carefully ornamented profile sections, such as Fig. XX, 2, require a considerable amount of time. The description of a map or the account of the geological history of the area can often be illustrated more adequately and far quicker by a number of sketch maps and sketch sections. A few of these, if carefully located and drawn with coloured pencils or showing the minimum number of beds necessary (*see* Fig. XX, 3), can bring out the geological features of an area much more quickly than pages of description illustrated by perhaps one profile section, which does not pass through all the features of interest.

Look for small areas on the map showing such features as unconformable relationships, oversteps, one set of faults shifted by and therefore earlier than another set, folds of distinctive character, intrusions cutting across the bedding or cut off by an unconformity and therefore pre-unconformity in age and so on. These are the evidence on which the geological history of the area is based. The sections are sketch in the sense that distances and heights are only approximately correct, but the relationships of the beds must be accurate.

For sketch maps do not copy the map laboriously in all its detail, but insert only the key beds, such as the Lower Greensand on the Brighton sheet (Fig. XX, 4).

Description of a Geological Map

A useful sequence to follow is given below:

1. Location of area.
2. Succession.
3. Main structural features.
4. Igneous rocks.
5. Relief.

1. *Location*

Relate the area of the map to the major geographical units of Britain. For the Brampton sheet 'The area shown includes part of the Vale of Eden to the west and, to the east, the extreme north-western portion of the Pennine Chain', and for the Brighton sheet 'The area shown includes the central part of the South Downs and the lower ground of the Weald to the north'.

2. *Succession*

Break the succession of beds present into units, separated by unconformities, e.g. Brampton sheet 'In the west there is a conformable succession of Triassic and Permian strata resting with marked unconformity along the centre of the sheet on a thick and conformable sequence of Carboniferous rocks ranging from the Coal Measures to the Cementstone Group', or for the Brighton sheet 'The Cretaceous rocks ranging from the Wadhurst Clay to the Upper Chalk are overlain with apparent conformity by a small thickness of Eocene beds'. (The wavy line in the legend at the base of the Reading Beds indicates a break here, but the map does not

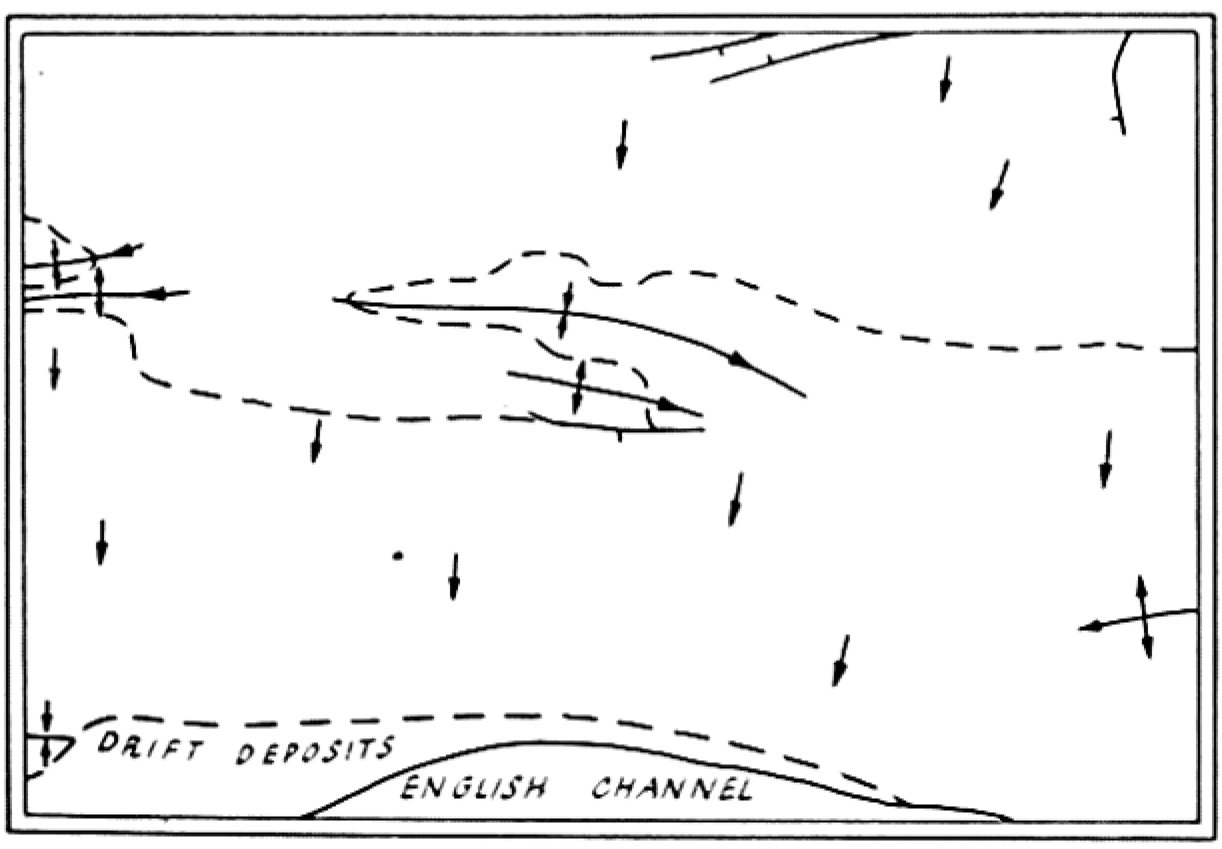


Fig. XX, 4.—Sketch Map Showing the Main Structural Lines of the Brighton Sheet

The broken line marks the base of the Lower Greensand, a 'key' horizon for indicating the main fold axes. The structures in the extreme south are hidden beneath a thick cover of drift deposits.

show any other evidence of unconformity.) 'Drift deposits include Clay with Flints on the Downs, gravels of various kinds on the low ground and Alluvium along the rivers'.

3. *Structure*

The treatment of this section will vary with the map. The essential features to be described as clearly and concisely as possible are:

(i) The direction of the general sheet dip of the rocks, whether it is steep or gentle, the presence of any major monoclinal flexures such as the steepening of dip all along the western margin of the Carboniferous beds of the Brampton sheet.

(ii) The position of the chief fold axes, whether they are symmetrical or not and any direction of pitch. A sketch map (*see* Fig. XX, 4) is often a great help.

(iii) The fault pattern of the area. If faults are few, as on the Brighton sheet, they can be described individually, but on a complexly faulted area like the Brampton sheet, it is necessary to generalize. State whether dip or strike faults are dominant, any evidence of relative age. Mention any major faults, such as the fault extending north to south down the centre of the sheet and the east to west fault on the south side of the Coal basin, throwing the Firestone Sill against the Middle Coal Measures, its down-throw therefore being approximately 1500 feet to the north. Examples of rifts, horsts, step faults, etc., can be given after the general pattern has been described.

(iv) Unconformity. If there is a major unconformity it may be possible to date certain faults, folds, etc., as pre- or post-unconformity. If possible state the direction of any oversteps.

4. *Igneous Rocks*

If these are present, describe their forms, i.e. dykes, sills, lava flows, vents, granite bosses, etc. Mention any evidence of age. Differences of trend and composition are often suggestive. On the Brampton sheet are two dykes, the one of augite-Andesite trending north-west to south-east and cutting Triassic rocks, the other of quartz-Dolerite, trending nearly east-west and cutting only Carboniferous rocks. The former must be post-Triassic and probably of Tertiary date, whilst it is reasonable to regard the other as older and of Armorican age.

5. *Relief*

Geographical students are far too apt to expand this section at the expense of structure. The structure of an area can be read only from a geological map, whilst to describe relief in detail it is necessary to refer to both geological and topographical maps, for the contours cannot often be followed easily on a geological map. The main points to be looked for are firstly the relationship of topography to 'structure'. See whether the relief is inverted or uninverted and which beds form scarps and headlands and which are more easily eroded. Secondly relate the drainage pattern of the area to 'structure'. Look especially for any cases of river capture or superimposition of drainage, such hydro-geological features as the number of dry valleys on the Chalk of the Brighton sheet should be mentioned.

In the description of a sheet it may be preferable to divide the map into two or more units and deal with each in turn rather than describing the map as a whole. On the Brampton sheet the areas composed dominantly of Carboniferous and Triassic rocks could be treated separately, but it is probably best not to subdivide the Brighton sheet. Each geological map presents a slightly different problem as regards the best method of description. The essential features to be looked for have been given and also an order of treatment that in many cases will be found satisfactory.

THE GEOLOGICAL HISTORY OF THE AREA SHOWN ON A MAP

The treatment must be chronological. The geological history can usually be divided into periods of sedimentation with perhaps some extrusive igneous activity, separated by episodes when the beds were folded and faulted and perhaps intruded by igneous rocks. An overstep was usually preceded by a period of erosion ending with the cutting of the surface of unconformity on which the younger beds were laid down. Finally the features of the present landscape were formed, mainly by erosion, but locally by deposition.

The map gives the evidence for folding and faulting, the nature of any igneous rocks, the presence of unconformities, but usually the conditions under which the beds were laid down cannot be inferred. An account of the geological history of the Brighton sheet should therefore not contain a long account of, for example, the nature and extent of the sea in which the Chalk was deposited, for this cannot be deduced from the map. The main points to be stressed are that the Cretaceous beds were deposited without any major breaks except for the eastward overstep of the Sandgate Beds on to the Weald Clay in the extreme east of the area. The basal Eocene rocks rest apparently conformably on the Upper Chalk. Then, probably in mid-Tertiary times, the area was folded and faulted, the pressure being from the south. The formation of the present landscape followed. Details of the structure and of interesting morphological features, such as the eastward deflection of the mouth of the Adur and the cliff line marked by the straight edge to the Coombe Deposits in the south-western corner, should be illustrated by sketch maps and sketch sections.

APPENDIX II

Suggestions for Further Reading

DEVELOPMENT OF GEOLOGY

Fenton, C. L. and Fenton, M. A. *Giants of Geology.* (Doubleday and Co., New York. 1952. 28*s.*)

Geikie, Sir A. *The Founders of Geology.* (MacMillan. 1905. Out of print.)

A. GENERAL GEOLOGY

Bailey, Sir E. B. and Weir, J. *Introduction to Geology.* (MacMillan. 1939. 18*s.*)

Blyth, F. G. H. *A Geology for Engineers.* (Arnold. 3rd Edition. 1952. 30*s.*)

Himus, G. W. and Sweeting, G. S. *The Elements of Field Geology.* (Univ. Tutorial Press. 1951. 12*s.* 6*d.*)

Holmes, A. *Principles of Physical Geology.* (Nelson. 1949. 30*s.*)

Lake, P. and Rastall, R. H. *A Text-book of Geology.* (Arnold. 5th Edition. 1949. 28*s.*)

Read, H. H. *Geology, An Introduction to Earth-History.* (Oxford Univ. Press. 1949. 6*s.*)

B. PHYSICAL GEOLOGY AND GEOMORPHOLOGY

Cotton, C. A. *Climatic Accidents in Landscape-Making.* (Whitcombe and Toombs. 1942. 32*s.* 6*d.*)

Cotton, C. A. *Landscape as Developed by the Processes of Normal Erosion.* (Cambridge Univ. Press. 2nd Edition. 1949. 47*s.* 6*d.*)

King, L. C. *South African Scenery. A Textbook of Geomorphology.* (Oliver and Boyd. 2nd Edition. 1951. 45*s.*)

Wooldridge, S. W. and Morgan, R. S. *The Physical Basis of Geography. An Outline of Geomorphology.* (Longmans. 1947. 26*s.*)

C. Petrology and Mineralogy

Bateman, A. M. *Economic Mineral Deposits*. (John Wiley, New York. 2nd Edition. 1950. 60*s*.)

Evans, J. W. and Davies, G. M. *Elementary Crystallography*. (Murby. 2nd Edition. 1948. 8*s*. 6*d*.)

Hatch, F. H., Rastall, R. H. and Black, M. *The Petrology of the Sedimentary Rocks*. (Murby. 3rd Edition. 1950. 22*s*. 6*d*.)

Hatch, F. H., Wells, A. K. and Wells, M. K. *The Petrology of the Igneous Rocks*. (Murby. 10th Edition. 1949. 25*s*.)

Rutley's *Elements of Mineralogy*. 24th Edition by H. H. Read. (Murby. 1949. 12*s*. 6*d*.)

Shand, S. J. *The Study of Rocks*. (Murby. 2nd Edition. 1947. 10*s*. 6*d*.)

Smith, H. G. *Minerals and the Microscope*. (Murby. 4th Edition. 1949. 6*s*. 6*d*.)

D. The Interior of the Earth, etc.

Daly, R. A. *Strength and Structure of the Earth*. (Prentice-Hall, New York. 1940. 28*s*.)

Holmes, A. (*See above*.)

Milne, J. *Earthquakes and other Earth Movements*. 7th Edition revised by A. W. Lee. (Kegan, Paul, Trench and Trubner. 1939. 15*s*.)

E. Palaeontology

Davies, A. M. *An Introduction to Palaeontology*. (Murby. 2nd Edition. 1951. 18*s*.)

Oakley, K. P. *Man the Tool-Maker*. (British Museum (Natural History). 1949. 2*s*. 6*d*.)

Oakley, K. P. and Muir-Wood, H. M. *The Succession of Life through Geological Time*. (British Museum (Natural History). 1948. 2*s*. 6*d*.)

Swinnerton, H. H. *Outlines of Palaeontology*. (Arnold. 3rd Edition. 1950. 32*s*. 6*d*.)

Woods, H. *Palaeontology, Invertebrate*. (Cambridge Univ. Press. 8th Edition. 1950. 18*s*.)

Stratigraphy

Wells, A. K. and Kirkaldy, J. F. *Outline of Historical Geology*. (Murby. 3rd Edition. 1952. 25*s*.)

Wills, L. J. *A Palaeogeographical Atlas of the British Isles and the Adjacent Parts of Europe*. (Blackie. 1951. 21*s*.)

F. Economic Applications

Blyth, F. G. H. (*See above*.)

Dixey, F. *A Practical Handbook of Water Supply*. (Murby. 2nd Edition. 1950. 35*s*.)

Fearnsides, W. G. and Bulman, O. M. B. *Geology in the Service of Man*. (Pelican Books. 1950. 1*s*. 6*d*.)

Jones, W. R. *Minerals in Industry.* (Pelican Books. 1945. 1*s.* 6*d.*)
Legget, R. F. *Geology and Engineering.* (McGraw-Hill. 1939. 55*s.* 6*d.*)
Schaffer, R. J. *The Weathering of Natural Building Stones.* (Building Research Special Report No. 18. H.M.S.O. 1932. 4*s.* 6*d.*)
Tiratsoo, E. N. *Petroleum Geology.* (Methuen. 1951. 42*s.*)
Walters, R. C. S. *The Nation's Water Supply.* (Ivor Nicholson and Watson. 1936. 31*s.* 6*d.*)

GEOLOGICAL MAPS

Platt, J. I. *Selected Exercises upon Geological Maps.* (Murby. 1951. 6*s.*)
Platt, J. I. and Challinor, J. *Simple Geological Structures. A Series of Notes and Map Exercises.* (Murby. 3rd Edition. 1951. 6*s.*)

LOCAL GEOLOGY

The Regional Guides of the Geological Survey (price 3*s.* 6*d.* and upwards) published by the Stationery Office provide excellent general accounts of Great Britain. The 1 inch to the mile maps (price 5*s.* per sheet for England and Wales and 7*s.* 6*d.* for Scotland) and the Sheet Memoirs (price 5*s.* and upwards) of the Geological Survey give more detailed information, but are not available for all parts of Great Britain. The Geological Survey publications can be obtained from the Stationery Office through any good bookseller.

The Proceedings of the Geologists' Association (Secretary, R. Reeley, Esq., Geological Survey and Museum, Exhibition Road, South Kensington, London, S.W. 7) contain accounts of Field Meetings held in many areas together with original papers. These Field Meeting Reports give the best routes for seeing the geology of the area, together with details of the more important sections.

The Geological Survey Museum is very well worth visiting and the Library is open to the public. Maps, memoirs and other books and periodicals can be consulted there, but cannot be borrowed. Members of the Geologists' Association can borrow maps, memoirs, etc. from the Association's Library, housed at University College, Gower Street, London, W.C.1.

N.B. All prices should be confirmed, whilst some of the books listed may be out of print.

Index-Glossary